Journal
of
The Franklin Institute
Devoted to Science and the Mechanic Arts

Vol. 262 DECEMBER, 1956 No. 6

# BENJAMIN RUSH'S COURSE IN CHEMISTRY AT THE YOUNG LADIES' ACADEMY

BY

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One of colonial Philadelphia's most important men and leading scientists was Benjamin Rush, physician and chemist. At the age of fourteen, in 1760, he took his B.A. at the school which later became Princeton. As was usual for the training of physicians in those days, he served as an apprentice and, after five and one-half years, sailed for Scotland to complete his training at the University of Edinburgh, which had one of the finest medical schools in the world at the time.

Having determined before leaving Philadelphia to be a candidate for the projected, but as yet non-existent, professorship of chemistry at the Medical School of the College of Philadelphia (now the University of Pennsylvania) he was careful to learn as much as possible from Dr. Joseph Black, probably the best British chemistry teacher at the time.

He received the degree of doctor of medicine from Edinburgh in 1768, then spent some months at the hospitals of London. After a visit to Paris he revisited London to study industrial chemistry in the factories. He returned to Philadelphia in July 1769 and on August 1st was elected the first professor of chemistry in the Medical School of the College of Philadelphia.

In those days a person teaching this subject had little of the needed teaching equipment with which to work. Fortunately, while Rush was in England he met Thomas Penn, proprietor of the Province of Pennsylvania, who asked him to take back to the college a gift of "a chymical apparatus . . . of great use . . . in the tryal of ores." [3]

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[3] Letter from Thomas Penn, May, 1769, to the Board of Trustees, University of Pennsylvania.

(Note—The Franklin Institute is not responsible for the statements and opinions advanced by contributors in the JOURNAL.

No American textbooks on chemistry existed and suitable ones from abroad were few in number. An earnest and dedicated teacher, Rush published an outline of his lectures, hoping thereby to make the learning of chemistry easier. His course was based on that of his master at Edinburgh, Joseph Black, and must have been of excellent quality.

The chair at the medical school brought him into prominence and he soon became one of America's leading physicians and an outstanding citizen—member of the Continental Congress, physician in the Continental Army and signer, on August 2, 1776, of the Declaration of Independence.

He never lost interest in teaching and the problems of education, writing essays and helping to found Dickinson College in 1773. About one century earlier a Frenchman by the name of Fenelon had proposed that girls be given a good education but no one seems to have paid much attention to his ideas, so that in Rush's time the education of women was largely ignored. Rush, however, appears to have been impressed by Fenelon's ideas and to have become partisan to them. In 1787 he saw an opportunity to contribute to this worthy cause and became one of the founders of the Young Ladies' Academy of Philadelphia, the first of its kind in our country and perhaps in the entire world. Its student body, at one time one hundred in number, came from practically all of the thirteen original states, as well as from Canada and the West Indies, but the greatest percentage was from Philadelphia and elsewhere in Pennsylvania. The curriculum included spelling, reading, writing, arithmetic, grammar, composition and geography.

In its first year, 1787, Dr. Rush gave the young ladies at the Academy a course in chemistry, consisting of twelve lectures. This is probably the first course in chemistry ever given to girls in America. The aim of the first seven lectures was to teach pure chemistry, the remaining five being given over to its application to cooking and home-making. In thus applying chemistry to home economics he most probably was scoring another "first" in American education. This endeavor on Rush's part was altogether laudable, for it represents an extra effort and tax upon the limited time of a man now grown important and busy. Perhaps because he was entirely too busy he was unable to give the course again, for we find no record that it was offered after the first year. He gave up the teaching of chemistry at the Medical School in the following year, probably for the same reason. At both schools he gave high calibre courses, but as a student of Black's he had a pattern which he could follow at the medical school, while none such existed for his course for the young ladies. Yet he drew up a set of very wise, though somewhat quaint aims,[4] which he stated in his first lecture, and tried hard to adhere to them. They show him to have had an educational philosophy of breadth and vision.

[4] See Windham Miles, "Benjamin Rush, Chemist," *Chymia*, Vol. 4, 1953, pp. 63–65.

Fortunately for the historian, there are in the possession of the Library Company of Philadelphia Rush's personally written notes and also the first eleven of his lectures to the young ladies, very carefully and completely written by a member of the class and later annotated by him. The lectures deal with the "Application of the Principles of Natural Philosophy and Chemistry to Domestic and Culinary Purposes" and are not only very clearly expressed, but even boast several demonstrations, which must have fascinated the girls.

The superior training under Dr. Black, added to a naturally alert and keen mind and the public recognition of his attainments in the form of his professorship at the Medical School would entitle him to be regarded as an authority in chemistry. Although he believed in the phlogiston theory at the time of his lectures, that would not make him appear out of date, for Lavoisier's oxygen theory was not published in book form until two years later, in 1789, and the "theory of the French chemists" was not widely adopted until some years later. Nevertheless not only the oxygen theory but the correct explanations for the spoilage of food substances and the spread of contagious diseases were not known to him. Thus even so famous and able a scientist as Dr. Rush could not help teaching many incorrect ideas. When we add the fact that he was a most sincerely religious man, whose piety very frequently shows itself in his utterances, we have a combination which can produce quaint teachings, as we shall see in the quotations which follow. Read from the vantage point of our own day the quotations make us wonder how we will sound to the chemists of the twenty-first century. We offer these selections from the notebooks on the course at the Academy not in a spirit of ridicule, but because we hope their quaintness and charm will prove both instructive and entertaining.

Our first selection shows a devout man in whom there is no conflict between religion and science. He is lecturing upon the atmosphere and breathing.

> Animal life exists five times as long in this dephlogisticated air [oxygen] as in common air—hence the advantage and refreshment of trees and other vegetables near our dwelling houses; and of frequently walking in gardens, planted with flowers, and other fragrant herbs. So enlivening is this air that, according to Milton, Satan himself was, for a moment, exhilarated, by breathing the pure air near the Garden of Eden.—The antediluvian air was exceedingly pure, perhaps, entirely dephlogisticated [pure oxygen]: there were then no marshes, fens nor lakes of stagnant and putrid water, to emit fogs and exhale noxious vapors.—Hence we may easily account for the surprising longevity of men before the flood. The new Heavens of which we read in the book of revelations means no more than a new atmosphere; that is one consisting entirely of pure air. [pure oxygen] This, like the pure water, will probably contribute to the health, and pleasure of the inhabitants of the new Jerusalem.

(To-day we have reason to believe that the "men before the flood" breathed air of the same oxygen content (21 per cent), as we do. If they had had to breathe "entirely dephlogisticated air," that is, pure oxygen, they would not have lasted very long.)

His reference, in the next excerpt, to the "Naples Grotto" shows that he had skill as a teacher, the story being obviously intended for a two-fold purpose: to hold the attention of his class and to show a practical application of the knowledge which he was imparting.

> Fixed air [carbon dioxide] produced from marble and vitriolic acid is found in cellars. [It is] extremely dangerous to go into cellars containing it. [A] person should hold [a] candle before him . . . if flame burns dimly or goes out he should start back instantly. [Tell the] story of Naples Grotto.

(The Naples Grotto is a cave called the "Grotto del Cane" in which the interior is lower than the entrance of the cave. A natural outflow of carbon dioxide constantly keeps the lower portion of the cave full of this gas. Therefore, any small animal which wanders into the cave will die for lack of oxygen when it reaches the region of the sunken floor. A human being however, or any other animal whose head is high enough to reach above the layer of $CO_2$, can walk in the cave without harm.)

In further reference to fixed air he speaks of "Pyrmont water," which, like our soda water, is a solution of carbon dioxide in water, and tells the following incredible story:

> . . . during the late war [the Revolutionary War] the troops stationed at Saratoga used pyrmont water, procured from a spring in that neighborhood, both as yeast and as a substitute for rum, of which they were destitute—they became very fond of it, and, it is said, were intoxicated by drinking it.

Priestley writes[5] that Sir John Pringle has informed him that from 8 to 10 drops of "Tinctura Martis" (tincture of iron) must be mixed with every pint to make artificial Pyrmont Water. Since the amount of alcohol in 10 drops of the tincture, per pint, is negligible, neither the artificial nor natural pyrmont (which contained no alcohol) could have produced intoxication. Either someone was being facetious with Dr. Rush, or he with the young ladies. (Could be some of the soldier boys found it a convenient excuse for over-indulgence in strong spirit!)

Although he was aware of "the advantage and refreshment of trees, and other vegetables, near our dwelling houses," he says that

> Trees planted about our houses are of great service, but if they be planted too thick, they will occasion damps and exhale noxious vapors at night.

In connection with his discussion of air, Rush makes wide application of this subject to sleep. He tells his class that a large room is nicer because the "dephlogisticated air" (oxygen) isn't confined to a small space (!) and is cooler in the summer and not so drafty in the winter. To our generation that would appear so obvious as to need no repetition and it would certainly be a waste of time to tell his

[5] "Directons for Impregnating Water with Fixed Air," etc., Joseph Priestley, London, 1772.

students, as he does, that "windows that open are nicer because you can open them top and bottom and get a draft."

To keep cool at night, he advises that "large beds are preferable because a person may move to the coolest part." He further advises wearing "a white hat with black or green lining," or placing a "handkerchief in the hat," "sitting still," application of "spirits of wine (alcohol) to the ears," "having a narrow entry." (An annotation reads: "William Rittenhouse's fact—he recovered from the languor and want of appetite occasioned by excessive heat and fatigue by eating a raw onion.") Rush says that the

> . . . dangerous practice of opening windows at night is to be strictly guarded against, for they admit noxious air which arises from fens, marshes, stagnant waters, streets, etc., besides, the weather may change while we sleep—hence the numerous train of intermitting fevers in Philadelphia in autumn.

On the subject of sleep, he feels that six hours should suffice, adding that two years' worth of activity could thus be added to a human life. He continues with a discussion of reasons for difficulty in sleeping:

> This is occasioned by cold feet. To remove this we should (1) either jump out of bed and stand for a few minutes on a cold hearth or (2), thrust our feet for a few minutes out of bed, or into a cold part of it (3), have a bottle or jug of warm water well-corked placed next to our feet in the bed during the night.
>
> Sleep is also prevented by an obstruction or an accumulation of perspiration causing restlessness and tossing from side to side. This disease is called the *cruels*. It is cured and sleep obtained by (1) first jumping out of bed and walking once or twice about the room and (2) by exposing the bed cloths [clothes] to the fresh air which have been filled with our perspiration—(3) by two assafetida pills as is the case of Wm. Armstrong. Sleep is sometimes prevented by anxiety of mind or a succession of new subjects of reflexion. In this case, it is to be sought for by (1) confining the attention steadily for some time to one subject—or (2) by counting 100 or 200 backwards or (3) by thinking upon the virtues of a living or departed friend.

Speaking on the subject of hydrogen, or "inflammable air," as it was then called, he not only confuses it with carbon monoxide and methane, which is to be expected, for chemists of the period were in darkness about the latter gases, but he makes the additional error of believing that gunpowder cannot be ignited by a flame:

> Inflammable air. This sort of air is extremely light and inflammable—hence it has a tendency to rise upwards; and raises balloons to an enormous height. It is procured from iron filings by means of the vitriolic acid—Fire damps in mines and caves is owing to the presence of inflammable air; [or carbon monoxide or methane—See above] this is capable of being set on fire by the blaze of a candle, not by sparks —on the contrary, gunpowder, which abounds with fixed air [carbon dioxide] cannot be set on fire with a blaze, but, may, by a spark.

His lecture on water contains the following passage:

> At certain seasons of the year, after a shower of rain has fallen, we often perceive the waters to be covered with a yellow scum and to emit a strong sulphureous smell:

this is produced by a yellow powder called pollen, contained in white lillies and other vegetables, which being tossed about by the winds, and carried up in vapour, condenses, and falls with rain—Another cause of the variety of colour in water is sand at the bottom; when water is not very deep, it will appear of the same colour as the sand; hence the red appearance of the water in the red sea, from red sand at its bottom.

Aside from the error implied in the vaporization and subsequent condensation of pollen, which could not survive the heat required to turn it into a gas, the ascription of the color of the Red Sea to the red sand at its bottom is a grave misstatement. The color is due to the presence of red algae, which grows in that body of water in sufficient abundance to make the water look red.

For those of our readers who like mystery stories we offer the following two excerpts:

Dr. Rodgers relates the fact of cabbage having once produced a fever at Oxford from putrifying near one of the colleges.

A ship sailed from England to Tortola, thence she returned to England; and made a second voyage to Tortola; during all these voyages a quantity of potatoes were suffered to remain in her hold, which by this time were completely putrified; and of ten sailors who went down into the hold, nine contracted fevers of which they all died owing to the noxious effluvia of the putrid potatoes.

We need hardly add that neither the biochemistry of putrefaction nor the germ theory of disease was known in Rush's time and he was voicing commonly held beliefs. Whatever the cause of these tragedies, it was not mere decomposition.

In those days, however, it was an accepted belief that disease was caused by putrefaction. Rush ascribed the frightful yellow fever epidemic of 1793 to gas coming from a pile of decomposing coffee which someone had thrown from a boat on the waterfront at Philadelphia.

His lecture on cleanliness in the household contains a few gems. For example, manufacturers of insecticides might like this idea:

Insects doubtlessly were designed by Providence to answer some useful purpose (certain it is that they are standing monuments to the fall of man; they tell us that we have forfeited our right to the earth and that while we are in this world we are in an enemy's country. They serve to exercise our humanity and patience and to promote cleanliness. Whenever they injure us however, we are justifiable in destroying them, by the principles of self-preservation).

The best method of destroying them [flies] is to put some molasses on a board, to which they will repair in swarms; a little gun-powder exploded under the board will destroy them. They may be drove out of a bedroom by a napkin.

(Some of us lazy people might prefer the insects to the irate neighbors produced by the explosion.)

And this one may appeal to exterminators:

If humanity revolts at putting them [rats] to death we may rid ourselves of them by banishing them thus: First catch one alive, hang a bell around its neck and let it go. They will all immediately be terrified and quit the house. 2. They may be banished also by shaving or singeing the hair of one of them.

On the subject of heat:

> Heat passes slowly through [is reflected? by] white bodies. Hence, the use of white hats and clothes in summer and hence the goodness of Providence in covering the heads of old people with white hair.
>
> The constant action of the sun, upon that part of the earth within the tropics, is supposed to have expanded it there, which accounts for its being an oblate spheroid.

(This would be "news" to physicists, who say that the earth's shape is due to the effect of the earth's rotation, which sets up a centrifugal force, thus creating a pull on its plastic interior. A hoop rotated very rapidly by a machine likewise bulges at its equator, due to centrifugal force.)

In his discussion of salt he says:

> The great Disposer of all things has so ordered it that these sea waters should be impregnated with salt for our own use. Also, to preserve them from putrefaction, from the numerous animals dying and vegetables rotting, at the bottom. Thirst may be removed at sea, after the fresh water has been expended, by placing the person in a barrel of sea-water, for the water, without any of its saline particles, will be imbibed by the pores.

We cannot tell whether this idea is just a wild belief or a "valid" claim by someone who tried it, but the very reverse would actually be true. The salt would withdraw fluids from the body and make a person even thirstier. Dr. Rush may have been told this tale by a jesting sailor at the waterfront.

His lecture on sulphur shows not only a sincere devotion to scripture, but a rich imagination as well. But the chemistry is correct.

> To melt gold, sulphur must be united with a fixed alkaline salt forming a compound called hepar sulphuris or liver of sulphur. [Potassium sulphide] This effectually dissolves gold when heated—[$2Au + K_2S_4 \rightarrow 2KAuS_2$] so as to make it soluble in water. This preparation is thought to be the means by which Moses dissolved the golden calf, idolatrously set up by the Israelites, which he caused them to drink. This being an exceedingly bitter solution was, in some degree, a punishment for their idolatry. Moses being skilled in the wisdom of the Egyptians, to whom chemistry was early known, very probably acquired his knowledge of this science among them.

The lecture on phosphorus is a good illustration of the vast changes which a revision in one chemical theory can bring about. Within two years Lavoisier's new oxygen theory was to give the world the correct explanation of all oxidation, of which the kindling of phosphorus is but one example. The fire-fly example completely ignores the searing effect upon the insect, if phorphorus were the cause of its luminescence. We now know that the latter is due to enzyme action and not to its being a "phosphoric animal" or its discharge of "large quantities of phlogiston."

> This [phosphorus] is composed of phlogiston feebly united with an acid and has the singular property of kindling into flame, spontaneously, when exposed to

the air for the phlogiston separates from the vitriolic acid, and unites with the air when admitted. Several bodies partake much of the phosphoric nature, such as light wood. The fire-fly is a phosphoric animal, and when flying, discharges large quantities of phlogiston—hence, the ocean frequently seems to be on fire. Meteors are bodies filled with phlogiston, which separates from them in their motion.

His analogy between calcination and the human soul gives another quaint illustration of his sincere piety.

By adding a body which abounds with phlogiston to this calx [any metal oxide] and melting, it may be restored to metal again: thus grease melted with calx of lead reduces it to lead. This calcination and reduction are truly emblematic of the resurrection of our bodies at the last day. The soul is, as it were, its phlogiston; when separated by death, the body becomes like the calx of metal, calcined, but, by the reunion with the soul it again resumes its ancient form.

For this one we leave it to the reader to make his own comment:

Remove a ring from finger if too little, without filing, by rubbing it with quicksilver, which will render it soft, that it may be broken in several pieces with a person's fingers.

A person would then be off to the jeweller's with the pieces, to be soldered together again. Why not simply have him make one saw-cut, remove the ring and solder it closed, after enlarging it? His method would involve first making an amalgam of the gold and mercury, then after breaking the ring into pieces, removing the mercury by annealing (which would damage any gems present), then making several solder-seams, since he would have "several pieces."

Speaking of kitchens he shows, once more, his gentleness of heart and concern for the welfare of others less fortunate. The occasion also provides him an opportunity to justify his stand for the education of women.

It is to be lamented that kitchens are too often the receptacles of dirt and what is worse, of vice. To prevent a communication of both, it has been recommended by some to have the kitchen at a considereble distance from the dwelling house. This in large families and in the present state of society, in this country, is impossible. If they are to be kept out of sight and hearing; the best place, in towns, is underground: if they be under the parlour, some springy body, as straw, may be placed under the parlour floor, to prevent the passage of sound. If they be the receptacles of dirt, vice, or ill manners, children should be carefully kept from them, for vice in a particular manner, like knowledge, is increased by being propagated. But is there no way of preventing this dirt or vice? Are our servants to be abandoned to destruction and ruin? No. (Our servants, to use the words of Lord Chesterfield, are "our unfortunate friends" or, to use the words of a higher authority, our "brethren"). There is one, and but one method of preventing the disorders of a kitchen and that is the presence of a mistress. The tongue, eye, and ears of a mistress in her kitchen are an effective remedy for all disorders. It is inconceivable what good effects would be produced by a lady visiting her kitchen two or three times a day. It would promote economy, and by that means give a wife a complete influence over her husband; for certain it is, that a man will love that woman most whose affection for himself he feels, everytime he sits down to a meal, or puts his hand in his pocket. Attention

of this sort will defend liberal and extensive knowledge from censure, for among the various illiberal reasons which have hitherto been given for neglecting the education of ladies, one has been that a liberal education renders ladies inattentive to domestic duties. How praiseworthy would it be in such ladies to show, by their conduct, that this remark is not only illiberal but also ill-founded.

He prescribes methods for preserving clothes, some of which suggestions are still in use; but we doubt very seriously whether dampness will preserve them (rather than hastening their deterioration), or that wrapping them in linen will be beneficial. As to the relation of "old or dirty" linens to "disease" and "exhalations from the skin," it is sufficient to point out that the germ theory of disease was not to appear for another century.

To prevent moths, mix some tobacco leaves, cedar shavings, alspice or camphor with them [the clothes] or what is a better method, pack them in trunks or chests and place them in the cellar, the dampness of which will preserve them or they may be kept safe by wrapping them in linen.

Linen clothes are not so healthy being liable when old or dirty to produce disease with the exhalations from the skin.

Enough-to-drive-the-fire-department-crazy, if widely tried:

Bed sheets, etc. should be well aired daily to discharge perspired matter which is much phlogisticated and exceedingly impure. This will be evident by taking a burning candle between two sheets any morning which have been lain in all night, for unless fresh air be admitted the flame will be immediately extinguished.

We have not made any experimental attempts to verify this claim, but we doubt if the carbon dioxide or, perhaps the de-oxygenated air (nitrogen), which he infers here, could be present.

Bleaching is done by the heat of the sun.

(It is not the heat, but certain constituents of the light of the sun.)

Ironing is done to smooth, or, as it were to polish the surface of the linen, etc. This is performed with hot irons: Great caution should be observed in putting the hands into cold water, when they are heated by this exercise: there have been instances of some dying in a few hours by this inconsiderate act.

(Again probably some legendary story.)

Dr. Rush was in serious error in his understanding of the chemistry of inks.

Ink generally gets blacker after it has been written with, by the evaporation of the water it contains.

(He probably meant an ink containing a ferrous salt, which darkens because of oxidation to ferric salt, not because of evaporation of water.)

Sympathetic ink which is used in private correspondence may be obtained by writing upon paper with a solution of *saccharum saturni* [lead acetate]; this writing when dry will disappear, but will immediately become legible, and of a brownish-black by holding it near the mouth of a bottle containing volatile *tincture of sulphur*

or liver of sulphur, [potassium sulphide] or a solution of orpiment—which is arsenic and sulphur—in lime water. The phlogiston emitted from these substances reduces the calx of the lead [lead oxide] and thus restores to it its natural dark color.

(Stumped by the phlogiston theory again! The secret ink becomes visible because of the formation of lead sulphide, not metallic lead.)

Something for the ladies on preserving beauty:

Washing the mouth and behind the ears, every morning with cold water is of great service to preserve teeth, health, and complexion.

Decay of the teeth is occassioned by a changeable climate. It is therefore prudent to sleep with the head warm; this is not only serviceable to our teeth, but also preserves the sight and hearing.

Lecturing on foods he makes suggestions, some wise, others not so. He shows, again, his pioneering interest in an intellectual approach to homemaking, as it relates to education for women.

There is the same relation between different aliments that there is between the notes of music, some agreeing and some disagreeing with each other. The perfection of cookery consists in finding out these relations. I am disposed to believe the science of cookery is still in its infancy and will remain so till it is rescued from the hands of practical cooks and made the subject of philosophical experiments and investigations. I believe there are pleasures to be enjoyed in eating and that there are degrees of health, and long life, to be dreived from the proper and harmonious mixture of aliments, that we are yet strangers to. Perhaps discoveries upon the subject may be reserved for some of the female philosophers of this new world.

I shall briefly explain what I mean by the harmony of aliments, by a few examples—*Bread and Meat* are related, and form a harmony when mixed together. Bread and milk, bread and butter, meat and salt, salted and fresh meat, mustard and cold beef, cabbage and vinegar [cole slaw], mutton and turnips, venison and currant jelly, pork and apple sauce are alike related to each other, alike grateful to the taste and alike healthy when taken in the stomach.

Let us next take a few instances of discord or the *want of harmony*, in aliments. *Fish and flesh*, when mixed together, bread and pudding, salt and sugar, meat and sweet sauce, butter and onion, milk and fish, are all contrary to each other and disagreeable to the taste; and if they do not offend the stomach it is owing to its peculiar strength and healthful [ness.]

Fermentation is an intestine motion between dissimilar bodies or dissimilar elements.

Which sets us thinking that:

Wonderful little, when all is said,
Wonderful little our fathers knew.
Half their remedies cured you dead—
Most of their teaching was quite untrue.
"Look at the stars when a patient is ill,
(Dirt has nothing to do with disease),
Bleed and blister as much as you will,
Blister and bleed him as oft as you please,"
Whence enormous and manifold
Errors were made by our fathers of old.[6]

[6] From "Our Fathers of Old" from *Rewards and Fairies*, by Rudyard Kipling. Copyright 1910 by Rudyard Kipling, reprinted by permission of Mrs. George Bambridge and Doubleday and Company, Inc.

*Acknowledgments and Sources*

1. To Dr. Wyndham Miles for calling our attention to the Rush note-books and for his very helpful suggestions during the preparation of this work.

2. To the Library Company of Philadelphia and to Mr. Barney Chesnick, Librarian, for permission to quote the Rush notebooks.

3. To Mr. Robert F. Sutton, Curator of the E. F. Smith Memorial Collection in the History of Chemistry, University of Pennsylvania.

4. Sources on Benjamin Rush:

(*a*) WYNDHAM MILES, "Benjamin Rush Chemist," *Chymia*, Vol. 4, 1953, pp. 37–77.

(*b*) L. H. BUTTERFIELD (Ed.), "Letters of Benjamin Rush," Princeton, 1951 (*Memoirs of the American Philosophical Society*, Vol. 30, 2 parts).

(*c*) GEORGE W. CORNER, "The Autobiography of Benjamin Rush," Princeton, Princeton University Press, 1948.

5. SIR WILLIAM RAMSAY, "Life and Letters of Joseph Black, M. D.," London, 1918.

**Cleaner for Magnetic Film.**—Trichlorotrifluoroethane, a chemical compound with a tongue-twisting name, originally developed as a refrigerant, has proved to be both safer and more efficient as a cleaner for magnetic sound-recording film than solvents now commonly used, according to the Du Pont Company.

Biggest advantages, Du Pont chemists have found, are its relative non-toxicity and the fact that, unlike many commonly used solvents, it will not soften the magnetic sound stripe or cause warping of the film base.

Under laboratory conditions, admittedly more rigorous than those encountered in commercial film-cleaning operations, common solvents caused sufficient softening of the sound stripe to affect its adhesion to the film base, resulting in peeling when the film was unreeled within an hour after cleaning. Certain solvents also showed a tendency to remove coloring incorporated in certain types of magnetic recording film.

From a safety standpoint, the Du Pont chemical compound, sold under the trademark "Freon-113," is both nontoxic and nonflammable.

**Power Plant for Vanguard Project.**—The flight test phase of Project Vanguard will make use of a modified Viking sounding rocket propelled by a rocket engine developed and produced by Reaction Motors, Inc., Denville, N. J. As in previous Viking rockets, launched by the Naval Research Laboratory in an upper atmosphere research program, the RMI powerplant will be of the liquid-propellant type, producing a rated thrust of 20,000 lb. Previous Viking single-stage rockets have reached a velocity of 4300 mph. and hold the world altitude record of 158 miles for single-stage rockets. RMI has recently completed the preparation of Viking powerplants for Martin's use in this Project.

The RMI-powered modified Viking to be used for Project Vanguard test will carry aloft a solid-propellant propulsion unit for the testing of the third-stage Vanguard rocket, according to N. Elliot Felt, Jr., Martin Company Operations Manager of Project Vanguard. Speaking before the Seventh Annual Astronautical Congress in Rome, Italy, Mr. Felt reported that a flight test program will be conducted at the Air Force Missile Test Center, near Cocoa, Florida, before the actual attempt is made to place an artificial satellite in orbit.

Project Vanguard is the name assigned to the Department of Defense logistical support of United States participation in the International Geophysical Year, July 1, 1957 to December 31, 1958, as announced by the White House on July 29, 1955. The Project was undertaken at the request of the U. S. National Committee for the IGY, established by the National Academy of Sciences which is sponsoring U. S. participation in the IGY, with support of the National Science Foundation.

Department of Defense support is on a three-service basis, with Navy management through the Chief of Naval Research, with the Naval Research Laboratory responsible for the technical program, which includes the three-stage launching vehicle, and the manufacturing, launching and initial radio-tracking of the earth satellite.

# TRANSIENT EFFECTS OF SUPPLY AND CONNECTING CONDUITS IN HYDRAULIC CONTROL SYSTEMS

BY

S. S. L. CHANG [1]

SYNOPSIS

Basic equations for transient flow of a slightly compressible fluid in a metal tubing are derived for both laminar and turbulent flow. Applying the equations to hydraulic control systems, it is shown (1) that the saturation limit of a valve controlled servomotor supplied by a conduit of length $l$ is considerably lower than its steady state value during the first $2l/c$ second following a step input, and (2) that the effects of connecting conduits in displacement controlled systems are to cause a dead time of $l/c$ second and to produce undesirable pressure echoes which can be eliminated by properly matching the conduits to the system as shown in the paper. The wave speed $C$ is approximately 5000 feet per second depending on the parameters.

## INTRODUCTION

In hydraulic control systems it is generally recognized that the fluid conduits should be kept as short as possible. However, in some applications, relatively long fluid conduits are necessary, either within the closed loop itself or in the supply system to the servomotor. An example of the former case is a system with variable displacement control where the controlled system is at a distance from the variable displacement pump. An example of the latter case is a valve controlled servomotor which is supplied by long conduits from the pressurized tank.

In previous analyses the pressure drop across the fluid lines is usually neglected. While this procedure is justifiable for relatively slow systems, it is not justifiable for fast systems where the response time is comparable to the travelling time of the pressure wave in the supply or connecting conduits. With ordinary hydraulic fluid, the transient pressure change in a tubing, say, of 10 ft. long is of the order of 50 times the steady state pressure change due to the same change in flow. In a fast system, it is the transient pressure variation which determines the system performance. Two cases of interest are analyzed in this paper:

1. Systems with long supply conduits: The effect of the large transient pressure drop is essentially a lowered velocity saturation limit of the servomotor. It can be improved by under-lapping the control valve.
2. Systems with long connecting conduits: There are two undesirable effects: (i) a "dead time" in which the system has absolutely no response, and (ii) multiple reflections which increase the settling time of the system.

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The first effect is unavoidable, but the second effect can be eliminated by properly terminating the lines. Equivalent electrical circuits are introduced as a means for properly matching the load to the connecting conduits.

## NOMENCLATURE

$A$ = hydro-mechanical conversion coefficient. It is the ram area for ram type servomotor and the displacement per radian for rotary type servomotor, in.$^2$ and in.$^3$/rad., respectively.
$b$ = conduit wall thickness, in.
$C_d$ = orifice discharge coefficient.
$c$ = speed of pressure wave, in./sec.
$D$ = conduit inside diameter, in.
$E$ = Young's Modulus, lb./in.$^2$
$F$ = wall friction, lb./in.
$F_L$ = load force or torque, lb. or lb.-in.
$f$ = friction factor, dimensionless.
$g$ = gravitational acceleration, 386 in./sec.$^2$
$k_b$ = bypass leakage coefficient, in.$^5$/lb.-sec.
$k_m$ = servomotor leakage coefficient, in.$^5$/lb.-sec.
$k_p$ = pump leakage coefficient, in.$^5$/lb.-sec.
$l$ = length of conduit, in.
$m$ = load mass or inertia, lb.-sec.$^2$/in. or lb.-in.-sec.$^2$
$p$ = pressure of mean flow in conduit, lb./in.$^2$
$p_0$ = steady state pressure, lb./in.$^2$
$p_m$ = counter pressure of servomotor, lb./in.$^2$
$p_s$ = steady state supply pressure to valve, lb./in.$^2$
$p_z$ = transient supply pressure to valve, lb./in.$^2$
$P_m = \frac{p_m}{p_s}$ = per unit counter pressure of servomotor
$P_z = \frac{p_z}{p_s}$ = per unit transient supply pressure
$q$ = mean flow in conduit, in.$^3$/sec.
$q_0$ = steady state flow in conduit, in.$^3$/sec.
$q_m$ = output flow to servomotor, in.$^3$/sec.
$q_{mm}$ = flow through valve at maximum stroke and $p_m = 0$, in.$^3$/sec.
$q_s$ = quiescent supply flow to valve, in.$^3$/sec.
$q_z$ = transient supply flow to valve, in.$^3$/sec.
$Q_m = \frac{q_m}{q_{mm}}$ = per unit output flow to servomotor, in.$^3$/sec.
$Q_z = \frac{q_z}{q_{mm}}$ = per unit transient supply flow to valve.
$q_p$ = pump displacement flow, in.$^3$/sec.
$q_d$ = servomotor displacement flow, in.$^3$/sec.
$Q_p(s)$, $Q_d(s)$ = Laplace transform of $\Delta q_p$, $\Delta q_d$, respectively.
$s$ = transform variable.
$t$ = time, second.
$u$ = mean fluid velocity in conduit, in./sec.
$u_0$ = steady state fluid velocity in conduit, in./sec.
$w$ = width of valve orifice, in.
$x$ = valve stroke, in.; or tilt angle of variable displacement pump.
$y$ = load displacement, in. or radian.
$Y(s)$ = Laplace transform of $y$.

$Z$ = characteristic hydraulic impedance of conduit, lb.-sec./in.$^5$
$Z_L$ = hydraulic impedance of load, lb.-sec./in.$^5$
$x$ = distance along conduit, in.
$\alpha$ = attenuation constant, in.$^{-1}$
$\beta$ = bulk modulus of elasticity of fluid lb./in.$^2$
$\Delta$ = prefix indicating a small change.
$\Gamma$ = coefficient of reflection.
$\rho$ = density of fluid, lb.-sec.$^2$/in.$^4$
$\mu$ = dynamic coefficient of viscosity, lb.-sec./in.$^2$
$\nu$ = kinematic coefficient of viscosity, in.$^2$/sec.
$\sigma$ = fluid cross-sectional area of conduit, in.$^2$
$\eta$ = load friction coefficient, lb.-sec./in. or lb.-in.-sec./radian.

### TRANSIENT FLOW CHARACTERISTICS OF SMOOTH PIPES

The transient flow characteristics in a smooth pipe are quite similar to wave propagation in free air. Due to the compressibility of hydraulic fluid, the pressure applied at one end of the pipe does not appear at the other end immediately but travels towards the other end at a constant speed.

There are three essential parameters, namely:

$$c = \text{velocity of propagation} = \left(\frac{\rho}{\beta} + \frac{D}{b}\frac{\rho}{E}\right)^{-\frac{1}{2}} \tag{1}$$

$$Z = \text{characteristic hydraulic impedance} = \frac{4\rho c}{\pi D^2} \tag{2}$$

$$\alpha = \text{attenuation constant} = \frac{16\nu}{D^2 C} \text{ (laminar flow)} \tag{3a}$$

$$\alpha = \frac{f u_0}{2DC} \text{ (turbulent flow)} \tag{3b}$$

Equations 1, 2, 3*a* and 3*b* are derived in Appendix I. Equations 3*a* and 3*b* are only approximately true for not too slow pressure variations with a frequency a few times larger than $\frac{16\nu}{\pi D^2}$ and $\frac{f u_0}{2\pi D}$, respectively. For very slow pressure variations, the attenuation constant is smaller than that given in the respective equations.

The physical significance of the parameters can be illustrated by the following example: Suppose there is a pressure change $\Delta p$ at the supply end. It will produce a flow change $\Delta q$ immediately at the same end, where $Z\Delta q = \Delta p$. Both variations will propagate along the pipe at speed $C$ which is usually much larger than the average fluid velocity $u_0$. As the pressure and flow variations propagate, both will decrease in magnitude at an exponential rate and $1/\alpha$ is the distance at which both $\Delta p$ and $\Delta q$ decrease to 36.7 per cent of their initial values.

Once the pressure change $\Delta p$ reaches a terminal it will be totally absorbed by the load if the hydraulic impedance $Z_L$ of the load is the

same as the characteristic impedance $Z$; otherwise $\Gamma\Delta p$ will be reflected back towards the source. The reflection coefficient $\Gamma$ can be calculated as

$$\Gamma = \frac{Z_L - Z}{Z_L + Z}. \tag{4}$$

If compressibility and inertia effects are present in the load, $Z_L$ and $\Gamma$ may be written in terms of the transform variable $s$, or in terms of $j\omega$ for sinusoidal waves.

To illustrate the magnitudes of the various parameters, the following typical values are assumed:

$D = 0.25$ in.
$b = 0.031$ in.
$\beta = 3 \times 10^5$ lb./in.$^2$
$\rho = 0.8 \times 10^{-4}$
$E = 16 \times 10^6$ lb./in.$^2$
$\nu = 0.02$ in.$^2$/sec.

Calculated values of $C$, $Z$, and $\alpha$ are:

$$C = 5.72 \times 10^4 \text{ in./sec.} = 4780 \text{ ft./sec.}$$

$$Z = \frac{0.8 \times 10^{-4} \times 5.72 \times 10^4}{\pi \times .125^2} = 93.2 \text{ lb.-sec./in.}^5$$

$$\frac{1}{\alpha} = \frac{0.25^2 \times 5.72 \times 10^4}{16 \times .02} = 11{,}200 \text{ in.} = 930 \text{ ft.}$$

Since $1/\alpha$ is many times the length of an average conduit, the dissipation effect is negligible in first approximation.

### TRANSIENT EFFECT OF SUPPLY CONDUITS

In a valve controlled system, the supply flow varies with input and load conditions. A sudden increase $\Delta q$ in the supply flow will cause a temporary decrease of $\Delta p = Z\Delta q$ of the supply pressure which eventually returns to its normal value since the steady state conduit loss is negligible. How long then will this pressure drop last? One may consider the situation as sending a step change in pressure $-\Delta p$ from the valve end to the supply end of the conduit. Since the supply tank is practically a constant pressure source with zero impedance, a reflected pressure rise $\Delta p$ will travel from the supply end to the valve end as soon as the pressure front $-\Delta p$ arrives. Therefore the total time interval between the instant of sudden increase in valve demand and the instant of arrival of the first reflected pressure front at the valve is $2l/c$, where $l$ is the length of the supply line. If the impedance offered by the valve to the supply line is equal to the characteristic impedance $Z$, the reflected pressure front will be totally absorbed by

the valve, and steady state condition will be reached at the end of the $2l/c$ interval. Otherwise, steady state condition will be approximately reached after a few reflections at a few times $2l/c$ second later.

From the above discussion, one sees that in the interval $2l/c$ following the initial disturbance, the relationship between the supply pressure and supply flow can be represented as

$$P_s = P_s + Z(q_s - q_s). \tag{5}$$

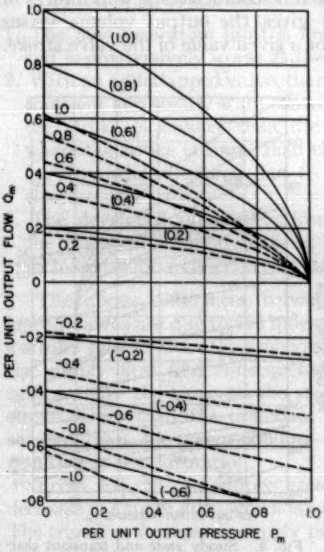


FIG. 1. Steady state and transient characteristics of closed-center valve,

$$\frac{Zq_{mm}}{p_s} = 1.$$

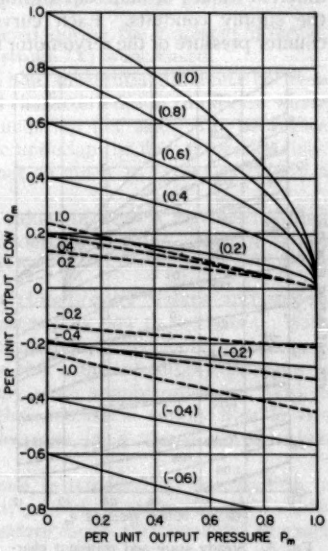


FIG. 2. Steady state and transient characteristics of closed-center valve,

$$\frac{Zq_{mm}}{p_s} = 4.$$

In a fast system which comes to rest with the control valve returned to its neutral position before the $2l/c$ interval is through, the reflected pressure change will not have any effect on the system load. One example of such a system is given by Shearer (1).[2] In his illustrative design of a valve controlled servomotor, the natural frequency of the servomotor including load inertia is 912 radians per second. If the supply conduit is 20 ft. long one way, the transient interval is $\frac{20 \times 2}{4780}$

[2] The boldface numbers in parentheses refer to the references appended to this paper.

= 0.0084 sec. The dimensionless time interval $\omega_{ns}t = 7.7$. As was shown by analog study (2), a well designed proportional control system will have already settled down at that instant following a unit step input. In such cases, Eq. 5 is adequate for the entire significant period. Another example is given by Lee (3) in which $\omega_{ns} = 8870$.

Figures 1, 2, 3 and 4 compare the steady state and transient performances of symmetrical 4-way valves with rectangular orifices and different values of underlap and different characteristic impedances of the supply conduits. Each curve gives the output volume versus counter pressure of the servomotor for a given value of the valve stroke.

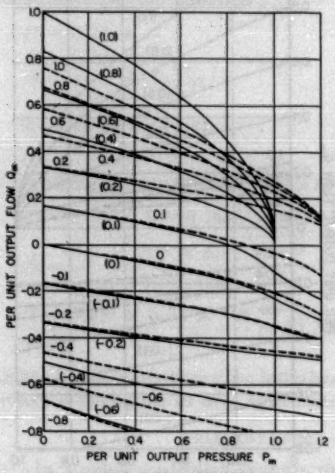


FIG. 3. Steady state and transient characteristics of valve with 20 per cent underlap, $\frac{Zq_{mm}}{p_s} = 1$.

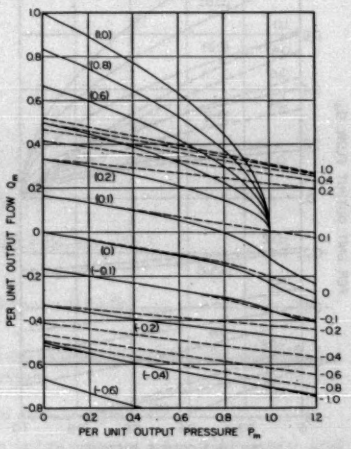


FIG. 4. Steady state and transient characteristics of valve with 20 per cent underlap, $\frac{Zq_{mm}}{p_s} = 4$.

The solid curves represent the steady state performance and are calculated with the assumption of constant supply pressure. The dotted curves represent the transient performance during the first $2l/c$ second and are calculated with the aid of Eq. 5. The values of the valve stroke associated with each curve are given in parentheses for the solid curves and without parentheses for the dotted curves. All the values of pressure, flow and stroke are in per unit terms with the normal supply pressure, maximum flow without motor counter pressure, and maximum stroke as the respective basic units.

The method used in calculating the curves is similar to that used

by Blackburn (4) and is given in detail in Appendix II. While this method is only approximate, it is nevertheless accurate enough to illustrate the general situation.

In Figs. 1, 2, 3 and 4 only the first and fourth quadrants of the flow versus pressure characteristics are given. The second and third quadrants can be obtained as reflections about the origin from the fourth and first quadrants respectively.

The following conclusions can be drawn from these graphs:

1. The flow saturation limit is lowered during the transient interval, and is progressively worse as the stroke (X) is increased.
2. With an underlapped valve, there is no substantial difference between transient and steady state control characteristics in the region where the stroke is smaller than the underlap per side. In the region where the stroke is larger than the underlap the flow saturation limit is substantially lowered, but to not as much an extent as that of a closed-center valve.
3. The developed pressure at low values of flow is increased during the transient interval with an underlapped valve, while it is not increased with a closed-center valve.

The above differences between closed-center valves and underlapped valves are due to the quiescent supply flow to the latter. With a stroke smaller than the amount of underlap, there is little change in the supply flow and consequently the transient supply pressure is substantially the same as the steady state supply pressure. With a stroke larger than the underlap, the increase in supply flow is also smaller than the corresponding increase in a closed-center valve, resulting in less saturation.

From Eq. 5, the supply pressure is temporarily increased by a decrease in supply flow, which is only possible in an underlapped valve. The transient increase in supply pressure causes the developed pressure to be higher.

The above differences point to the advantage of underlapped valves during the transient interval. One may point out the non-linear steady state flow versus stroke characteristics as a disadvantage. However, this nonlinearity is due to our assumption of a rectangular orifice and is in no way inherent in an underlapped valve. For instance, one may shape the orifice in such a way that its width is 50 per cent in the region where $x < \mu$ and 100 per cent in the region where $x > \mu$. For such a valve, the values of $X$ in Figs. 3 and 4 become $X = 0$, $\frac{1}{6}$, $\frac{3}{6}$, $\frac{3}{6}$, $\frac{4}{6}$, $\frac{5}{6}$, and 1 instead of $X = 0.1$, 0.2, 0.4, 0.6, 0.8, and 1, respectively.

The situation is more complicated in intermediate cases in which the $2l/c$ interval is a fraction of the settling time of the system. One may depict the valve characteristics as a set of lines which move from the

dotted lines to the solid lines after the $2l/c$ interval. However, such phenomena are probably too complicated for manual analysis.

As an illustration of the various magnitudes involved, let us consider a four way valve which gives a maximum flow of 10 in.$^3$/sec. with normal supply pressure of 1000 lb./in.$^2$. If the supply tubing is of $\frac{1}{4}$-in. inside diameter, as given in the previous example, the transient impedance ratio is

$$S = \frac{93.2 \times 10}{1000} = 0.932 \approx 1.$$

The corresponding pressure drop for a 20-ft. tubing due to steady flow of 10 in.$^3$/sec. is approximately 50 lb./in.$^2$, which is negligible compared to the normal supply pressure of 1000 lb./in.$^2$.

### TRANSIENT EFFECT OF CONNECTING CONDUITS

In a transmission system where the servomotor is connected by conduits of appreciable length to the variable displacement pump, a change in pump displacement will not be felt by the servomotor until $l/c$ second later. Since this is an unavoidable effect, the primary concern here is the matching of the conduit to the pump and servomotor to prevent multiple reflections in the conduits. A mathematical expression which describes the dynamics of the system, will also be derived.

The following assumptions are made:

1. The check valves used in the system for maintaining proper pressure ranges can be considered closed or non-existent in so far as the transient response is concerned.
2. The average absolute pressure in the system is high enough so that cavitation does not occur.
3. Direct leakages of pump and motor are small enough so that they can be treated as parts of differential leakages without introducing appreciable error.
4. Additional by-pass is required to increase the damping ratio of the servomotor.

Electrical symbols are borrowed here to indicate various types of flow. Assuming the analogy between voltage, current, pressure, and flow, Table I gives the correspondence between the hydraulic and electrical cases.

The equivalent electrical circuit of a hydraulic transmission system is shown in Fig. 5. The characteristic line impedance is $2Z$ to account for both conduits. If the line is perfectly matched at the motor end, there will be no reflection. If the line is perfectly matched at the pump end, the reflected pressure wave will be completely absorbed once it arrives at the pump end and will not have any effect on the load system.

TABLE I.

| Types of Flow | Mathematical Expression Hydraulic | Electrical | Symbol |
|---|---|---|---|
| Pump displacement flow | $q_p$ | current generator | |
| Compressibility flow | $q_c = \frac{V}{B}\frac{dP}{dt}$ | $i = C\frac{de}{dt}$ | |
| Leakage flow | $q = kp$ | $i = \frac{e}{R}$ | |
| Servomotor displacement flow $q$ and load system | $p = \frac{\eta}{A^2}q + \frac{m}{A^2}\frac{dq}{dt} + \frac{F_L}{A}$ | $e = R_i + L\frac{di}{dt} + e$ | |

However, it is generally impossible to match the line impedance at the motor end. The time constant $m/\eta$ is usually too large and the load disturbance is unpredictable. At the pump end, due to the large reflected mass and rigidity of the driving system the current generator can be considered as an open circuit as far as impedance is concerned. The volume of a rotary type variable displacement pump is quite small. Both considerations make it possible to match approximately the line impedance at the pump end.

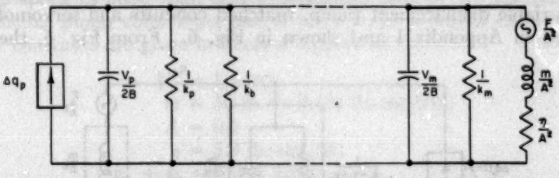


FIG. 5. Equivalent electrical circuit of a hydraulic transmission system.

It is advantageous to put the capillary by-pass at the pump end for the following considerations: (1) it allows a conduit of lower characteristic impedance to be used, reducing the transient back pressure encountered by the pump; and (2) it reduces the time constant due to compressibility at pump end (Eq. 9).

Approximate impedance matching at the pump end requires that

$$2Z = \frac{1}{k_p + k_b}. \tag{6}$$

Equations 6 and 2 determine the inside diameter of the conduit to be

$$D = \sqrt{\frac{8\rho C}{\pi}(k_p + k_b)}. \tag{7}$$

The inside diameters of commercial tubings are standardized, however, the choice of $k_b$ is quite flexible. Once the approximate value of $D$ is determined from Eq. 7 by assuming a suitable value for $k_b$, a standard tubing size can be selected and the exact value of $k_b$ to use is calculated from Eq. 8

$$k_b = \frac{8\rho C}{\pi D^2} - k_p. \tag{8}$$

The degree of perfection of the impedance matching at the pump end can be indicated by its transient as well as frequency response. It is shown in Appendix I that if a unit step pressure wave arrives at the pump end, the only trace of reflection is $e^{-t/T_p}$ where

$$T_p = \frac{V_p}{4\beta(k_p + k_b)}. \tag{9}$$

If $T_p$ is very small compared to $1/\omega_s$, the reflection has negligible effect on the servomotor. From the frequency response point of view the impedance matching can be considered practically perfect if

$$\omega_c T_p \ll 1 \tag{10}$$

where $\omega_c$ is the gain cross over frequency.

The equivalent circuit of a hydraulic transmission system including the variable displacement pump, matched conduits and servomotor is derived in Appendix I and shown in Fig. 6. From Fig. 6, the dis-

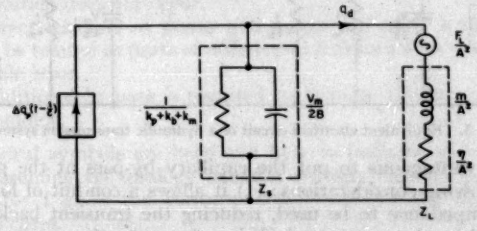


FIG. 6. Simplified equivalent circuit of a hydraulic transmission system with conduits matched at pump end.

placement flow of the servomotor can be calculated as the superposition of two flows which are due to the variable displacement pump and load force, $F_L$, respectively. In terms of Laplace Transform, it is

$$Q_d(s) = \frac{Z_s Q_p(s)\, e^{-ls/c}}{Z_s + Z_L} - \frac{\frac{F(s)}{A}}{Z_s + Z_L}$$

$$= \frac{Q_p(s)\, e^{-ls/c} - \frac{1}{Z_s}\frac{F(s)}{A}}{1 + Z_L \cdot \frac{1}{Z_s}}$$

$$= \frac{Q_p(s)\, e^{-ls/c} - \left(k_p + k_b + k_m + \frac{V_m}{2\beta}s\right)\frac{F(s)}{A}}{1 + \left(\frac{\eta}{A^2} + \frac{m}{A^2}s\right)\left(k_p + k_b + k_m + \frac{V_m}{2\beta}s\right)}. \qquad (11)$$

The load displacement is

$$Y(s) = \frac{Q_d(s)}{sA} = \frac{AQ_p(s)\, e^{-ls/c} - \left(k_p + k_b + k_m + \frac{V_m}{2\beta}s\right)F(s)}{A^2 + \left(k_p + k_b + k_m + \frac{V_m}{2\beta}s\right)(\eta + ms)}. \qquad (12)$$

Shearer's (1) ram type servomotor is used here to illustrate the various magnitudes involved. Without a hole in the ram, $k_m$ can be considered as practically zero. The volume of the variable displacement pump is assumed to be 0.2 cu. in. per side. This should be ample considering that the irreducible portion of this volume is only one fourth of the maximum displacement per revolution. Assuming a pump speed of 3600 rpm. and a maximum flow of 3.9 in.$^3$/sec., the irreducible pump volume per side is $3.9/4 \times 60 = 0.0162$ cu. in. The other constants are given in Shearer's paper as below:

$$V_m = 1.5 \text{ in.}^3$$
$$m = 50 \text{ lb.} = 0.130 \text{ lb.-sec.}^2/\text{in.}$$
$$A = 0.5$$
$$\eta = 5.9 \text{ lb.-sec./in.}$$
$$k_p + k_b = 3.3 \times 10^{-3}.$$

The time constant $T_p$ is

$$T_p = \frac{0.2}{4 \times 3 \times 10^5 \times 3.3 \times 10^{-3}} = 5 \times 10^{-5} \text{ sec.}$$

$$\omega_c T_p < \omega_{n_2} T_p = 0.0456 \ll 1.$$

The required diameter of the conduits is:

$$D = \sqrt{\frac{8 \times 0.8 \times 10^{-4} \times 5.92 \times 10^4 \times 3.3 \times 10^{-3}}{\pi}} = 0.20 \text{ in.}$$

In closing, it should be mentioned that in a vast majority of cases, the conduits are short enough so that matching of the characteristic impedance of the conduits to the terminal impedances is relatively unimportant compared to other considerations. A crucial criterion seems to be the relative magnitudes of the travel time $l/c$ and the settling time of the closed loop system. If $l/c$ is much smaller than the settling time, the fluid volumes of the pump, the motor and the conduits can be lumped into a single elastance (5,6), and the dead time due to the conduits can be neglected.

## APPENDIX I

### DERIVATION OF BASIC EQUATIONS

The problem being considered is the flow of a slightly compressible fluid in a circular pipe with uniform cross-section but slightly elastic walls. The change of momentum due to flow $u\frac{\partial(\rho u)}{\partial z}$ is assumed to be negligible compared to the change of local momentum $\frac{\partial(\rho u)}{\partial t}$. The assumption is later justified as the ratio of the magnitudes of the two terms is approximately $u/c$. Similarly, $\rho$ and $\sigma$ can be treated as constants when multiplied by $u$ or $p$ since the percentage variations in $\rho$ and $\sigma$ are negligible compared to percentage variations in $u$ and $p$.

The equation expressing the rate of change of momentum of the fluid is:

$$\rho A\frac{\partial u}{\partial t} = \rho\frac{\partial q}{\partial t} = -\sigma\frac{\partial p}{\partial z} - F. \tag{13}$$

The wall friction $F$ is simply $\frac{32\mu}{D^2}u$ for laminar flow. For turbulent flow, it is assumed that the turbulence is fully developed and has reached a balance with the mean flow at all times. The assumption is justifiable as the mixing length $L_T$ of turbulent flow is only a small fraction of the pipe diameter, and $L_T/u$ is of the order of $10^{-4}$ sec., while the period of the pressure wave is at least $10^{-3}$ sec. The wall friction can be written as

$$F = \frac{f}{D}\frac{u^2}{2g}\cdot\rho g\sigma = \frac{2f\rho}{\pi D^5}q^2 \tag{14}$$

where the friction coefficient $f$ is a function of the Reynolds number and smoothness of wall surface (7).

While $F(q)$ is not a linear function for turbulent flow, it can be linearized if $\Delta q$ is considered as a small variation superimposed on a constant flow $q_0$. Then

$$F(q_0 + \Delta q) = F(q_0) + \frac{dF(q_0)}{dq_0}\Delta q. \tag{15}$$

Equation 13 becomes

$$\rho\frac{\partial\Delta q}{\partial t} = -\sigma\frac{\partial p_0}{\partial z} - \sigma\frac{\partial\Delta p}{\partial z} - F(q_0) - \frac{dF(q_0)}{dq_0}\Delta q = -\sigma\frac{\partial\Delta p}{\partial z} - \frac{dF(q_0)}{dq_0}\Delta q. \tag{16}$$

The second equality sign is due to the fact that pressure drop and wall friction cancel out for constant flow. For large Reynolds number, $f$ is a constant, and

$$\frac{dF(q_0)}{dq_0} = \frac{4f\rho q_0}{\pi D^5} = \frac{\rho f u_0}{D}. \tag{17}$$

Therefore Eq. 13 can be written as

$$\rho\frac{\partial\Delta q}{\partial t} = -\sigma\frac{\partial\Delta p}{\partial z} - \rho\eta\Delta q \tag{18}$$

where $\eta$ is a constant and is equal to $32\nu/D^2$ for laminar flow or $fu_0/D$ for turbulent flow.

Due to conservation of fluid mass:

$$\rho \frac{\partial \Delta q}{\partial z} = -\frac{\partial (\rho\sigma)}{\partial t} = -\frac{d(\rho\sigma)}{dp}\frac{\partial \Delta p}{\partial t}. \tag{19}$$

The derivative $\frac{d(\rho\sigma)}{dt}$ can be evaluated in terms of bulk modulus and Young's modulus and Eq. 19 becomes

$$\frac{\partial \Delta q}{\partial z} = -\sigma\left(\frac{1}{\beta} + \frac{D}{bE}\right)\frac{\partial \Delta p}{\partial t}. \tag{20}$$

Solving for $\Delta p$ and $\Delta q$ from Eqs. 18 and 20, one obtains

$$\frac{\partial^2 \Delta p}{\partial t^2} + \eta \frac{\partial \Delta p}{\partial t} = \frac{1}{\left(\frac{1}{\beta} + \frac{D}{bE}\right)}\frac{\partial^2 \Delta p}{\partial z^2}, \tag{21}$$

and an identical equation for $\Delta q$. Equation 21 is a one dimensional wave equation in a dissipative medium. The wave speed is

$$C = \left(\frac{\rho}{\beta} + \frac{D\rho}{bE}\right)^{-\frac{1}{2}}. \tag{22}$$

For sinusoidal pressure wave $\Delta p = \mathbf{p}\, e^{-j\omega t}$, where $\mathbf{p}$ is a function of $z$ only, Eq. 21 become

$$\frac{1}{C^2}(-\omega^2 - j\omega\eta)\mathbf{p} = \frac{\partial^2 \mathbf{p}}{\partial z^2}. \tag{23}$$

Hence

$$\mathbf{p} = \hat{p}\, e^{\pm j\omega/c(1+j\eta/\omega)^{\frac{1}{2}}}$$

$$\approx \hat{p}\, e^{\pm(j\omega/c - \eta/2c)}. \tag{24}$$

The approximation holds if $\omega \gg \eta$. $\hat{p}$ is a complex constant. Eq. 24 represents travelling waves in the $z$ and $-z$ directions, respectively, with an exponential decay rate of $\alpha$ nepers per unit length of travel, where

$$\alpha = \frac{\eta}{2c}. \tag{25}$$

It is shown in the illustrative calculations that $\alpha$ is very small. Neglecting the dissipative term, Eqs. 18, 20, and 21 can be written as

$$\frac{\partial \Delta q}{\partial t} = -\frac{\sigma}{\rho}\frac{\partial \Delta p}{\partial z} \tag{26}$$

$$\frac{\partial \Delta q}{\partial z} = -\frac{\sigma}{\rho C^2}\frac{\partial \Delta p}{\partial t} \tag{27}$$

$$\frac{\partial^2 \Delta p}{\partial t^2} = C^2 \frac{\partial^2 \Delta p}{\partial z^2}. \tag{28}$$

Equations 26, 27, and 28 are readily solved for the transient response. Assume that a transient pressure variation $\Delta p = f_1(t)$ is applied to the $z = 0$ terminal of a very long conduit extending to the positive $z$-direction. As reflected wave is physically ruled out, the solution of Eq. 28 for $\Delta p$ along the conduit is

$$\Delta p = f_1\left(t - \frac{z}{c}\right). \tag{29}$$

From Eqs. 26 and 27

$$\Delta q = \frac{\sigma}{\rho C} f_1\left(t - \frac{z}{C}\right) = \frac{\sigma}{\rho C}\Delta p = \frac{\Delta p}{Z}. \tag{30}$$

Eqs. 22, 30 and 25 are the same as Eqs. 1, 2, and 3, respectively.

Next, the situation when a pressure wave arrives at a terminal is considered. The variation in terminal pressure is

$$\Delta p_T = \Delta p_i + \Delta p_r \tag{31}$$

where $\Delta p_r$ is the reflected pressure wave. The variation in flow from the conduit to the load is

$$\Delta q_T = \Delta q_i - \Delta q_r = \frac{1}{Z}(\Delta p_i - \Delta p_r). \tag{32}$$

If the hydraulic impedance at the terminal is $\frac{\Delta p_T}{\Delta q_T} = Z_L$, Eqs. 31 and 32 can be solved for the reflection coefficient $\Gamma = \frac{\Delta p_r}{\Delta p_i}$ and is given in Eq. 4.

Equation 4 can be interpreted in the sense of Laplace transform and used to determine the reflected transient wave. Consider a terminating load consisting of a leakage path equal to the characteristic impedance $Z$ and an elastance $Vs/\beta$ in parallel. The coefficient of reflection is

$$\Gamma(s) = \frac{Z_l - Z}{Z_l + Z} = \frac{\frac{1}{Z} - \frac{1}{Z_l}}{\frac{1}{Z} + \frac{1}{Z_l}} = \frac{\frac{Vs}{\beta}}{\frac{2}{Z} + \frac{Vs}{\beta}} = \frac{s}{s + \frac{2\beta}{ZV}}. \tag{33}$$

With a unit step incident pressure wave, the reflected pressure wave is

$$\Delta p_r(t) = L^{-1}\left[\frac{s}{s + \frac{2\beta}{ZV}} \cdot \frac{1}{s}\right] = e^{-(2\beta/ZV)t}. \tag{34}$$

Equation 34 is the same as Eq. 9.

To obtain a relation between the terminal pressure and flow, Eqs. 31 and 32 can be written into another form

$$\Delta p_T + Z\Delta q_T = 2\Delta p_i. \tag{35}$$

Referring to Fig. 5, if $k_p + k_b = \frac{1}{2Z}$, and the effect of the elastance $\frac{V_p}{2\beta}$ is negligible, one half of the variations in pump displacement will flow into the conduit. Therefore $\Delta q$ at the pump end is $\frac{\Delta q_p}{2}$. The incident pressure variation at the motor end for each conduit is

$$\Delta p_i = \frac{Z\Delta q_p\left(t - \frac{l}{c}\right)}{2}. \tag{36}$$

Equation 35 can be written as

$$\Delta q_T = \frac{2\Delta p_i}{Z} - \frac{2\Delta p_T}{2Z} \tag{37}$$

$$= \Delta q_p\left(t - \frac{l}{c}\right) - (k_p + k_b)2\Delta p_T. \tag{38}$$

Since $2\Delta p_T$ is the net pressure variation across the servomotor and $\Delta q_T$ is the variation of flow into the servomotor, Eq. 38 represents the pump conduit combination as an idealized variable displacement pump with delayed action shunted by a leakage path of $k_p + k_b$. It is illustrated in Fig. 6.

## APPENDIX II

The pressure versus flow curves of Figs. 1 to 4 are derived from Bernoulli's equations. For the steady state condition, variation in supply pressure due to pipe friction is neglected. For the transient condition, Eq. 5 is assumed.

There are two cases to be considered:

*Case 1: Closed-Center Valve*

With a closed-center valve, the flow passes through two identical orifices in series, and half of the net pressure is applied to each orifice. Bernoulli's equation for the flow is

$$q_m = C_d W X \sqrt{\frac{1}{\rho}(p_s - p_m)}. \tag{39}$$

In wide open position, without any load pressure, the steady state flow is

$$q_{mm} = C_d W X_m \sqrt{\frac{p_s}{\rho}}. \tag{40}$$

It is chosen as the basic unit for flow. Eq. 39 can be written in per unit terms. Dividing Eq. 39 by Eq. 40

$$Q_m = X\sqrt{P_s - P_m}. \tag{41}$$

For the steady state condition, $P_s = 1$, and Eq. 41 gives the set of solid curves in Figs. 1 and 2.

For the transient condition $P_s = 1 - \frac{Zq_{mm}}{p_s} Q_m$, and Eq. 41 can be written as

$$P_m = 1 - \frac{Zq_{mm}}{p_s} Q_m - \left(\frac{Q_m}{X}\right)^2.$$

The dotted curves in Figs. 1 and 2 are calculated from Eq. 42.

*Case 2: Under-Lapped Valve*

With a stroke larger than or equal to the amount of underlap, the case is similar to Case 1. Essentially the same derivation gives:

$$q_{mm} = C_d W(u + x_m)\sqrt{\frac{p_s}{\rho}}. \tag{43}$$

For the steady state flow

$$Q_m = \frac{U + X}{U + 1}\sqrt{1 - P_m}. \tag{44}$$

and for the transient flow:

$$P_m = 1 - \frac{Zq_{mm}}{p_s}\left(Q_m - \frac{U}{1 + U}\right) - \left(\frac{U + 1}{U + X}\right)^2 Q_m^2. \tag{45}$$

With a stroke smaller than the amount of underlap, all four orifices are open. The flow through the two large orifices is

$$q_1 = C_d w(u + x)\sqrt{\frac{1}{\rho}(p_s - p_m)}. \tag{46}$$

The flow through the two small orifices is

$$q_2 = C_d w(u - x)\sqrt{\frac{1}{\rho}(p_s + p_m)}. \tag{47}$$

The supply flow and output flow are, respectively;

$$q_s = q_1 + q_2 \tag{48}$$

$$q_m = q_1 - q_2. \tag{49}$$

Equations 46 to 49 can be written in per unit terms. They are

$$Q_1 = \frac{U+X}{U+1}\sqrt{P_s - P_m} \tag{50}$$

$$Q_2 = \frac{U-X}{U+1}\sqrt{P_s + P_m} \tag{51}$$

$$Q_m = Q_1 - Q_2 \tag{52}$$

$$Q_s = Q_1 + Q_2. \tag{53}$$

For the steady state condition, $P_s = 1$, and $Q$ can be calculated from Eqs. 50 to 52. For the transient condition, Eq. 5 gives

$$P_s = 1 - \frac{Zq_{mn}}{p_s}\left(Q_s - \frac{U}{1+U}\right). \tag{54}$$

Solution of the above equations by eliminating variables leads to a fourth order equation. However, direct numerical calculations are quite simple. One may assume a value of $P_s$ and calculate $Q_s$ from Eqs. 50, 51 and 53. A better approximation for $P_s$ is then obtained from Eq. 54. The above processes are repeated until two successive values of $P_s$ agree.

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# THE DESIGN OF THE MACKINAC BRIDGE FOR AERODYNAMIC STABILITY

BY

D. B. STEINMAN[1]

## INTRODUCTION

The $99,800,000 Mackinac Bridge in Michigan, under construction 1954–57, represents a triumph of the new science of suspension bridge aerodynamics. The design of the bridge, with a main span of 3800 ft., was predetermined scientifically, in final form, without spending years in groping, cut-and-try experimentation and without successive modification of design to overcome aerodynamic instability. Now, three years after adoption of the design (Fig. 1) and award of construction contracts of record magnitude, extensive wind-tunnel tests have been completed on a large-scale dynamic model of the bridge. No modification of the design has been found necessary or desirable. The wind-tunnel tests show conclusively that the Mackinac Bridge, as designed, has complete and absolute aerodynamic stability against all forms of oscillation (vertical, torsional, and coupled) in all modes, *at all wind velocities and all angles of attack.*

These test results for the design of the Mackinac Bridge may be summarized in a single phrase: *perfect aerodynamic stability.* This goal has never before been attained or approximated in any bridge section previously investigated.

With the startling destruction of the Tacoma Narrows Bridge in 1940 by cumulative catastrophic oscillations in a mild gale, the engineering profession was awakened to the imperative importance of considering the aerodynamic problem in bridge design. In striving to resist these potential destructive forces, the more obvious, elementary methods ordinarily pursued tend to produce structures that are needlessly extravagant in cost and clumsy in proportions. In the case of the Mackinac Bridge, a different course was adopted. A bridge of ideal, assured aerodynamic safety has been secured without sacrificing either economy or graceful proportions. By scientific design, utilizing the new knowledge of suspension bridge aerodynamics, the Mackinac Bridge has been made the most stable suspension bridge, aerodynamically, that has ever been designed.

This result has been achieved, not by spending millions of dollars to build up the structure (in weight and stiffness) to resist the *effects*, but by scientific design of the cross-section to eliminate the *cause* of aerodynamic instability. The vertical and torsional aerodynamic

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forces tending to produce oscillations are not merely resisted; they are scientifically *eliminated*.

This paper is written to present and explain the fundamental principles and the simple methods whereby these results have been achieved.

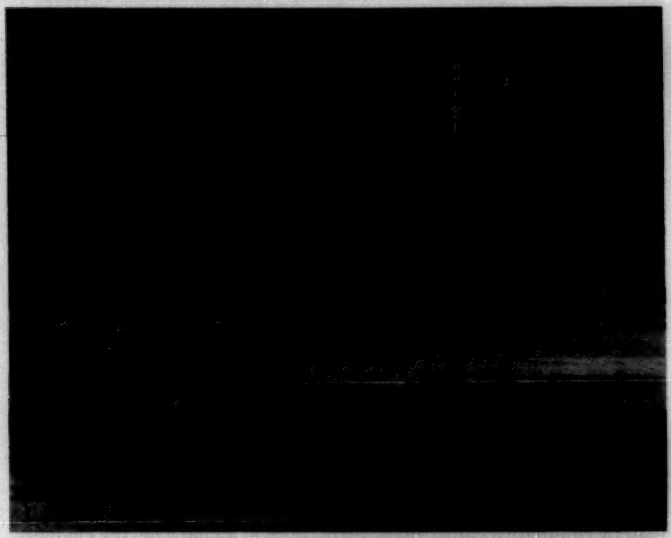


FIG. 1. Perspective drawing of the Mackinac Bridge. The suspension bridge, 8614 ft. long, has a main span of 3800 ft.

## FUNDAMENTAL PRINCIPLES

The scientific achievement of an economical design of complete aerodynamic stability for the Mackinac Bridge is a confirmation of the soundness of basic scientific and mathematical conclusions.

The fundamental principles are as follows:

1. The phenomena of aerodynamic instability are not a mystery but can be reduced to predictive scientific analysis and prevention. A *science* of bridge aerodynamics is a reality.

2. It is more scientific (and more economical) to eliminate the *cause* of aerodynamic instability by scientific design than to build up the structure, in weight and stiffness, to resist the *effects* of aerodynamic instability. The unscientific procedure results in structures that are needlessly clumsy and extravagant.

3. All bridge cross-sections do not behave alike, aerodynamically. They may be predictively differentiated and classified as aerodynamically *stable* and *unstable* sections, of different degrees of stability or instability, in the three different kinds of potential oscillation (vertical, torsional, and coupled).

4. The aerodynamic characteristics of any proposed bridge section are either already known or may be predictively determined by *simple model tests* on a small-scale section model. Expensive, time-consuming wind-tunnel tests on a full bridge model or on an elaborate large-scale oscillating section model are not required in predetermining the design. It is unscientific and unnecessary to spend years in groping experimentation with successive, cut-and-try modifications of design.

5. The aerodynamic behavior of a bridge may be qualitatively and mathematically *predicted* from the simple lift and torque graphs previously recorded for different sections or obtained for a new section with a small-scale static section-model in a small wind tunnel. The slopes of the graphs determine stability or instability. The curvature of the graphs determines limiting amplitudes.

6. The ideal bridge section, aerodynamically, is one that has *zero slope* of both the lift graph and the torque graph. Zero slope in both graphs denotes complete elimination of the lift forces and moments that produce aerodynamic oscillations, vertical, torsional, and coupled.

7. Bridges of assured aerodynamic stability may be economically secured by *simple modifications* of the usual bridge sections.

## SIMPLE MODEL TESTS

Based on fundamental conceptions of the aerodynamic forces and moments acting on a bridge section, simple modifications of the conventional bridge cross-section have been devised to eliminate the concentrations of differential pressure and the surfaces on which those pressure differences acted. These modified sections were easily and inexpensively tested and developed by means of simple, home-made office models, suspended from light springs and exposed to the breeze from an electric fan.

The results of these elementary tests on inexpensive office models, confirmed and refined by tests quickly made on a small-scale non-oscillating section model in a small wind tunnel, provided the basis for the design adopted for the Mackinac Bridge.

The confirmatory tests on a small-scale section model of the Mackinac Bridge were made for the writer by Professor F. J. Maher in the small wind-tunnel at Virginia Polytechnic Institute. The model, only $8\frac{1}{2}$ in. wide and 15 in. long, was constructed by Prof. Maher to represent a 120-ft. length of bridge to a scale of $\frac{1}{8}$ in. to the foot. The model was built to scale in accordance with the cross-section shown in Fig. 2. Open-grid sections of the deck and open railings were simulated

in the model by use of wire screening. Graphs giving the variation of aerodynamic lift, drag, and moment with the angle of attack of the wind for this stationary section model were plotted. These three graphs supplied the information to assure the aerodynamic stability of the bridge. The total cost of the model and the tests was only $500.

### DESIGN FEATURES FOR AERODYNAMIC STABILITY

The essential special features characterizing the design of the Mackinac Bridge for assured aerodynamic stability are shown in the cross-section, Fig. 2.

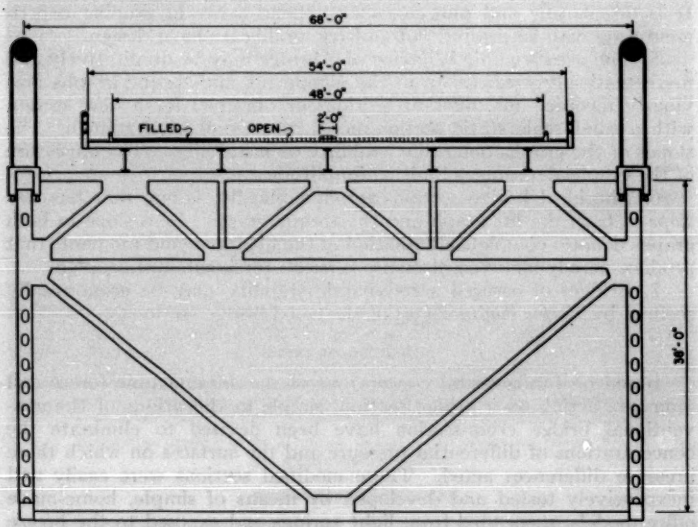



FIG. 2. Cross-section of the Mackinac Bridge, designed for the highest degree of aerodynamic stability.

The outstanding original feature contributing the high aerodynamic stability is the provision of wide open spaces between the stiffening trusses and the outer edges of the roadway. The trusses are spaced 68 ft. apart and the roadway is only 48 ft. wide, thus leaving open spaces 10 ft. wide on each side, for the full length of the suspension bridge. These wide lateral openings are located where the maximum aerodynamic pressure differences would otherwise be concentrated; such pressure differences ordinarily produce the critical alternating vertical forces inducing and amplifying *vertical* oscillations, together with the

maximum lever-arms for these vertical forces in inducing and amplifying *torsional* oscillations. These lateral openings serve a dual purpose:

1. They equalize the aerodynamic pressures above and below the deck in these critical areas adjacent to the stiffening trusses or girders, thereby cancelling the resultant alternating vertical forces.

2. They remove the area of solid deck on which these pressure differences would otherwise act. A pressure cannot exist and cannot produce a force without an area on which to act. (Force equals pressure times area; at one stroke we eliminate both factors in this product.)

The alternating pressure differences ordinarily concentrated in these corners of a bridge cross-section not only create the biggest alternating lift forces causing cumulative amplification of *vertical* oscillations, but they also operate with maximum leverage to produce the alternating torques causing cumulative amplification of *torsional* oscillations.

For further perfection of the aerodynamic stability of the Mackinac design, the equivalent of a wide longitudinal opening is provided in the middle of the roadway. (See Fig. 2.) The outer lanes, each 12 ft. wide, are made solid, and the two inner lanes and the center mall (24 ft. of width) are made of open-grid construction (of the safest, most improved type).

Simple model tests have shown that a design with open grid over the full width of the roadway does not produce aerodynamic stability. The solid deck, or a substantial part of it, is needed for atmospheric damping, to act against oscillations by atmospheric resistance. The Mackinac Bridge cross-section provides the solution. The two solid roadway lanes, each 12 ft. wide, supply the necessary atmospheric damping. Even in the two open lanes, a large measure of atmospheric damping is preserved by the friction of the airflow through the grid, with the velocity of this airflow augmented by the effect of the adjacent solid deck.

Wind-tunnel tests (the original small-scale static model tests and the more recent large-scale oscillating model tests) have confirmed the unprecedentedly high aerodynamic stability of this design of cross-section, combining the two outer openings with an opening in the middle of the roadway.

An additional design feature introduced for the still further perfection of the aerodynamic stability of the Mackinac Bridge is the use of open-web, trussed floorbeams (see Fig. 2) instead of the usual solid-web floorbeams. Aerodynamic oscillations of bridges have usually started under the action of quartering winds, blowing at angles of approximately 45 deg. to the axis of the bridges; the longitudinal component parallel to the bridge axis and acting on the transverse floorbeams and on the arched camber of the span, tends to start the oscillations; and the

transverse component, acting across the span, then amplifies the initial oscillation if the cross-section has aerodynamic instability. The use of open floorbeams eliminates an important origin for the *initiation* of oscillations by gusts and quartering winds. The aerodynamically stable cross-section eliminates the *amplification* of oscillations, whether originated by gusts or by the imperceptible vibrations due to traffic. Any initial vibration or tremor is quickly *damped*, instead of being sustained and amplified.

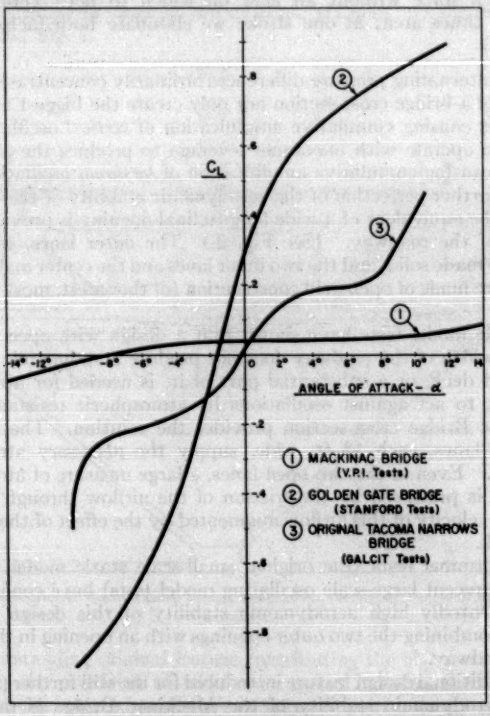

$C_L$
ANGLE OF ATTACK- $\alpha$
① MACKINAC BRIDGE (V.P.I. Tests)
② GOLDEN GATE BRIDGE (STANFORD Tests)
③ ORIGINAL TACOMA NARROWS BRIDGE (GALCIT Tests)

FIG. 3. Comparison of static lift graphs for three suspension bridges.

### SLOPE OF STATIC LIFT GRAPH

The static lift graph is simply obtained by plotting the measured vertical lift force on a small section model held stationary at various angles of attack in a wind tunnel.

For comparison and contrast, the static lift graphs for three significant bridge sections are shown, superimposed and plotted to the same scale, in Fig. 3. The corresponding static torque graphs, for the same three bridges, are shown in Fig. 4. Taken from official records and published reports, the graphs for the Golden Gate Bridge were obtained in the wind tunnel at Stanford University, the graphs for the original (1940) Tacoma Narrows Bridge were obtained in the Guggenheim Aeronautic Laboratory of the California Institute of Technology, and the graphs for the Mackinac Bridge were obtained in the small wind tunnel at Virginia Polytechnic Institute.

The slope of the static lift graph represents the rate of increase of vertical lift with angle of attack. (A small correction, the "drag correction," is made in the plotted graphs in order to take into account the fact that the model is inclined, instead of the wind direction, to provide the various small angles of attack.)

The slope of the static lift graph is significant. A *negative slope* (lift decreasing with increasing angle of attack) would represent dangerous, *catastrophic instability* in vertical oscillations. A bridge section possessing this characteristic would be subject to cumulative amplification of vertical oscillations to catastrophic amplitudes.

A *positive slope* of the static lift graph identifies "stable" sections, so designated merely to distinguish them from "catastrophically unstable" sections. This distinction is clear-cut in the case of narrow geometric sections, such as lenticular sections, with the depth exceeding the width. In bridge cross-sections, however, a "stable" section, that is, one with positive slope of the lift graph, is subject to limited aerodynamic oscillations in certain critical ranges of wind velocity. These aerodynamic oscillations usually occur at low wind velocities. Although they are not "catastrophic," these low-velocity oscillations are alarming, and they tend to shorten the life of the bridge by fatigue. This is the type of oscillation, commonly known as "galloping," which characterized the ill-fated Tacoma Narrows Bridge (1940) during the four months of its life.

In both cases, catastrophic instability (negative slope of lift graph) and limited instability (positive slope of lift graph), *the degree of instability is proportional to the slope of the lift graph*. The steeper the slope, the greater is the rate of amplification of the oscillations. The rate of increase is logarithmic, like a rate of compound interest applied cumulatively at each oscillation. The smallest tremor is automatically amplified a thousand-fold to an amplitude of one or more feet in a few minutes.

In all of the formulas for aerodynamic instability, the degree of instability (measured by the rate of amplification or speed of building up vertical oscillations) is found to be proportional to the *slope* of the static lift graph.

Since the foregoing established relationship applies to all lift graphs, of either positive or negative slope, the conclusion is clear:

*The ideal bridge section is one that has zero slope of static lift graph.*

In this respect, the goal sought in an ideal bridge section is quite different from the objective sought in wing sections for airplanes. "Flight stability" is something quite different from "aerodynamic stability." In the case of airfoil design, the objective sought is maximum lift, and the ideal airfoil is one that yields maximum ratio of vertical lift to horizontal drag. The idealized airfoil has a steep lift graph, with a slope of +6.28. The ideal bridge section should have a flat lift graph with a slope of *zero*.

The foregoing important distinction is overlooked by those who seek to apply the formulas of conventionalized airfoil theory to bridge sections, since airfoil theory assumes that the section is an idealized airfoil of fixed characteristics, including steep slope or lift graph. Such misapplication of inappropriate theory and formulas fails to give due credit to the more stable bridge sections, scientifically designed, in which slope of lift graph is greatly reduced or eliminated.

In Table I are listed the comparative slopes of the static lift graphs (corrected for drag) for some notable bridge sections; the idealized airfoil and the ideal bridge section are included for comparison.

TABLE I.—*Slope of Static Lift Graph.*

| | |
|---|---|
| Golden Gate | +10.5 |
| (Idealized Airfoil | + 6.28) |
| George Washington | + 6.2 |
| Tacoma (Original) | + 5.5 |
| Bronx-Whitestone | + 5.0 |
| *Mackinac* (Grid Covered) | + 1.9 |
| *Mackinac* (Grid Open) | + 0.03 |
| (Ideal Bridge Section | 0) |

For the Mackinac Bridge as designed (see Fig. 3 and Table I) the slope of lift graph is +0.03, virtually zero. This degree of perfection has never before been approximated or attained.

This remarkably flat slope (+0.03) of the Mackinac lift graph should be compared with the comparatively steep slopes of the lift graphs (+5.0 to +10.5) recorded for prior large suspension bridges, and with the steep slope (+6.28) for the idealized airfoil.

Using the slope of lift graph as a measure of vertical instability, Table I shows that the Mackinac Bridge, as designed, is *350 times safer than the Golden Gate Bridge* against vertical oscillations or "galloping."

For completeness of presentation, Table I also includes the hypothetical case of the Mackinac Bridge with the grid in the middle of the roadway (24 ft. of width) assumed completely covered, as by ice and

snow. Even for this extreme assumed condition, the slope of lift graph has the unprecedentedly low value of +1.9, or $5\frac{1}{2}$ times as safe as the corresponding figure (+10.5) for the Golden Gate Bridge. Moreover, for this assumed extreme condition, the ice and snow packed in the meshes of the grid and any ice and snow on the solid portions of the deck would greatly increase the structural damping, thereby offsetting the effect of the small increase in the slope of the lift graph.

The recently completed large-scale wind-tunnel tests on a model of the Mackinac Bridge in the specially built laboratory at the University of Washington confirm the fact that the Mackinac Bridge has complete and absolute aerodynamic stability against *vertical* oscillations at all wind velocities (to infinity) and at all angles of attack.

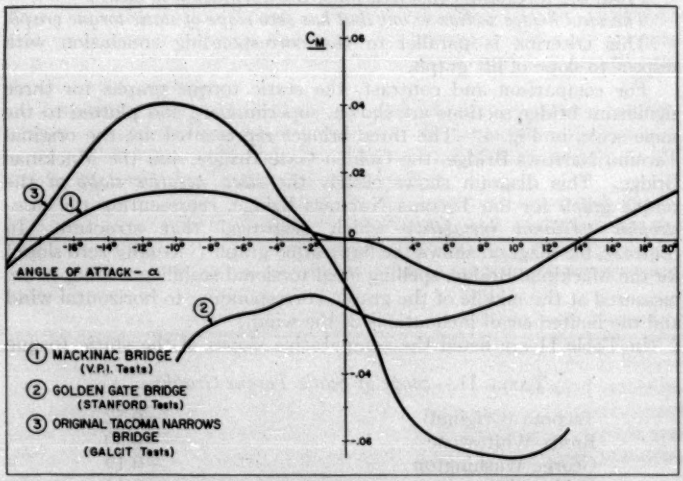



FIG. 4. Comparison of static torque graphs for three suspension bridges.

### SLOPE OF STATIC TORQUE GRAPH

For the static torque graph, as in the consideration of static lift graphs, *the ideal slope is zero*. Zero slope of torque graph means the elimination and complete absence of all forces and moments tending to induce and to amplify torsional (twisting) oscillations.

In all of the formulas for torsional instability, the logarithmic increment (or rate of amplification) is found to be proportional to the *slope* of the static torque graphs. (The complete mathematical analysis utilizes, in addition, a supplementary static torque graph obtained with a curved model of the cross section.)

In addition to the steepness of the slope, the direction of the slope is of critical significance. A *negative* (downward) slope of torque graph identifies *catastrophic torsional instability*. This is the dangerous type of instability that was revealed in the torsional oscillations that destroyed the Tacoma Narrows Bridge on November 7, 1940.

A *positive* (upward) slope of torque graph identifies a so-called "stable" section in torsion, but such "stable" section is also subject to potential aerodynamic oscillations in torsion. In this case the aerodynamic oscillations are non-catastrophic; they are of limited amplitude (from a few inches to several feet) and they occur at low wind velocities. Even such limited oscillations are troublesome and alarming, and they weaken the structure by fatigue.

From the foregoing considerations, the conclusion is clear:

*The ideal bridge section is one that has zero slope of static torque graph.*

This criterion is parallel to the corresponding conclusion with respect to slope of lift graph.

For comparison and contrast, the static torque graphs for three significant bridge sections are shown, superimposed and plotted to the same scale, in Fig. 4. The three bridges represented are the original Tacoma Narrows Bridge, the Golden Gate Bridge, and the Mackinac Bridge. This diagram shows clearly the *steep negative slope* of the torque graph for the Tacoma Narrows Bridge, representing the *catastrophic torsional instability* which destroyed that structure. In contrast, the diagram shows the flat torque graph (virtually zero slope) for the Mackinac Bridge, spelling ideal torsional stability. (Slopes are measured at the middle of the graph, corresponding to horizontal wind and the limited small inclinations of the wind.)

In Table II are listed the comparative slopes of the static torque

TABLE II.—*Slope of Static Torque Graphs.*

| | |
|---|---|
| Tacoma (Original) | −0.52 |
| Bronx-Whitestone | −0.50 |
| George Washington | −0.19 |
| Golden Gate | −0.13 |
| *Mackinac* (Grid Open) | −0.02 |
| *Mackinac* (Grid Covered) | 0 |
| (Ideal Bridge Section | 0) |
| (Idealized Airfoil | +1.57) |

graphs for some notable bridge sections; the idealized airfoil and the ideal bridge section are included for comparison.

Of the sections listed in Table II, the idealized airfoil is the only one represented by a *positive slope* of torque graph. For bridge sections, a *zero slope* or a *slight negative slope* is preferable. If the lift graph and the torque graph both have a positive slope, the section is vulnerable to

*coupled* oscillations, representing a dynamic combination of automatically synchronized vertical and torsional oscillations. In the case of airfoils (airplane wings and tail surfaces), such coupled oscillations, known as "flutter," are a source of danger and have repeatedly proved disastrous. That is why zero slope of lift and torque graphs (or a *slight* positive slope of lift graph combined with a *slight* negative slope of torque graph) represents the ideal for bridge sections, eliminating all possibility of *vertical*, *torsional*, and *coupled* instability.

Using the respective slopes listed in Table II as a measure of torsional instability, the tabulation shows that the Mackinac Bridge, as designed, is 26 times safer against torsional oscillations than the original Tacoma Narrows Bridge, 25 times safer than the Bronx-Whitestone Bridge, 9.5 times safer than the George Washington Bridge, and 6.5 times safer than the Golden Gate Bridge. For the hypothetical case of the grid completely covered by ice and snow, the foregoing ratios are actually improved, yielding an *infinite ratio* of superior torsional stability for the Mackinac section.

Combining the data of Tables I and II, as a measure of safety against *coupled* oscillations, the Mackinac Bridge section, as designed, is 6.5 to 350 times safer than the Golden Gate Bridge, and 26 to 183 times safer than the Tacoma Narrows Bridge.

The graphs (Figs. 3 and 4) show how a section of assured, predetermined aerodynamic stability was selected and confirmed for the Mackinac Bridge. This simple procedure is the key to the safe, speedy, scientific design of future suspension bridges for assured aerodynamic stability.

The recently completed large-scale wind-tunnel tests on a model of the Mackinac Bridge in the specially built laboratory at the University of Washington confirm the fact that the Mackinac Bridge has complete and absolute stability against *torsional* oscillations at all wind velocities (to infinity) and at all angles of attack. The large-scale wind-tunnel tests also show that the Mackinac Bridge, as designed, has complete and absolute stability against *coupled* oscillations at all wind velocities (to infinity) and at all angles of attack.

### DEPTH OF STIFFENING TRUSS

A suspension bridge ignorantly designed, or one otherwise unsafe aerodynamically, may be made safe by the crude and simple device of providing extravagantly excessive depth of the stiffening girder or truss.

By a published formula, the required truss-depth for the 3800-ft. span Mackinac Bridge (if it were unscientifically designed) would be 46 ft., or 1/82 of the span. But this depth would be extravagant in cost and wasteful of steel.

For the Mackinac Bridge we adopted an ultra-conservative truss-depth of 38 ft., yielding a convenient ratio of 1/100 of the span. In

view of the assured, high aerodynamic stability of the design, a shallower truss-depth would have been entirely safe. In fact, the Associate Consultant, Mr. Glenn B. Woodruff, stated that, in view of the aerodynamically safe design, he would be satisfied with a truss-depth of 12 ft. for the Mackinac Bridge.

In a suspension bridge, when correctly designed, the cost increases steeply with increasing depth of stiffening truss. By reducing the depth from 46 ft. to 38 ft., several million dollars were saved. A further reduction of depth would have saved more millions of dollars, and would have been amply safe.

Merely because there are many who do not know or understand the fundamental principles of the aerodynamic problem and its solution, the writer had to be ultra-conservative and to forego the additional cost-saving through any further reduction of truss-depth. A barrage of uninformed criticism and attack had to be overcome. It was necessary to make certain sacrifices in order to retain the confidence of the public, the investors, and the insurance companies. The ultra-conservative design was the price that had to be paid in order to sell the project.

### A DOUBLE LATERAL SYSTEM

As a further contribution to assured ultra-safety of the aerodynamic design of the Mackinac Bridge, a double system of lateral bracing was incorporated. By providing two planes of horizontal bracing, at or near the planes of the top and bottom chords of the stiffening trusses, respectively, and extending over the full length of the suspension bridge, we secure the integral effect of a hollow rectangular section in torsion. The torsional stiffness of the structure is thereby greatly augmented, together with a corresponding high increase in the structural damping in torsion.

For the Mackinac Bridge, in the light of the scientific design of the cross-section to eliminate any trace of aerodynamic instability, the extra high measure of torsional resistance secured by providing a double lateral system was really not necessary. It was provided in order to be ultra-conservative, as an additional concession to public confidence.

By the addition of the extra plane of lateral bracing, the torsional rigidity of the Mackinac Bridge was increased *seven-fold*, from 115,000 lb. to 832,000 lb., against one-segment oscillation (the main span assumed to deflect in a single segment); and nearly *fourteen-fold*, from 160,000 lb. to 2,200,000 lb., against two-segment oscillation (the main span assumed to deflect in two segments, the mode that wrecked the Tacoma Narrows Bridge).

As a direct result of the many-fold increase of torsional stiffness contributed by the provision of a double system of lateral bracing, the calculated frequency ratios (ratios of theoretical harmonic frequency in

torsional oscillation to theoretical harmonic frequency in vertical oscillation) exceeded 3.5. These high (favorable) frequency ratios were unprecedented and exceeded the available range of the test equipment in the aerodynamic laboratory at the University of Washington. New modifications of the equipment had to be devised and installed before the Mackinac Bridge model could be tested.

The abnormally high calculated frequency ratios for the Mackinac Bridge, resulting from the provision of a double lateral system, constitute a further safeguard against any possibility of *coupled* oscillations. On account of the high frequency ratios, the required wind velocity for such coupled oscillations, even if they were possible, would be fantastically high.

FIG. 5. Dynamic model used in the wind-tunnel tests at the University of Washington. Accurately built to 1/50 scale, the model represents a 253-ft. section of the Mackinac Bridge.

### TESTS CONFIRM THE HIGH AERODYNAMIC STABILITY

Soon after the Mackinac Bridge bonds were sold and the contractors were notified to proceed with the construction of the bridge, arrangements were concluded in March, 1954, for a thorough aerodynamic investigation to be conducted by Professor F. B. Farquharson in the Suspension Bridge Laboratory at the University of Washington. The

purpose of these additional tests was to secure impartial, authoritative confirmation of the high degree of aerodynamic stability achieved in the design of the bridge. These investigations, costing $15,000, were completed and the results recorded in Professor Farquharson's Final Report, dated May 20, 1955.

The model used for these wind-tunnel tests was a 1/50-scale section-model, 60.75 in. long, with details of shape reliably duplicated. (See Fig. 5.) The tests were made in a specially built open-jet wind tunnel with a wind-jet 12 ft. long and 4 ft. high.

The extremely high aerodynamic stability of the Mackinac Bridge exceeded all prior experience in aerodynamic investigations. Professor Farquharson had to revise his test equipment when he found that this bridge had features of stability much higher than had ever been previously investigated. In fact, some of the features of stability of the Mackinac Bridge, such as the very high frequency ratio of 3.5 and the high estimated damping of 0.10 (for the iced condition), were actually too high to be fully duplicated in the model.

When the model was tested for the normal operating condition of the structure, namely, with the grids in the central portion of the roadway and the sidewalks open, absolutely no motion developed at any angle of attack up to the extreme value of $\pm 20$ deg. (the limits of the wind tunnel) and over the full range of velocities available. These tests were conducted under very low damping conditions (0.005) which would reveal any slightest trace of instability; the actual structural damping in the bridge will be ten to twenty times as high (0.05 to 0.10), yielding further emphasis to this tested confirmation of *complete aerodynamic stability*.

The wind-tunnel tests showed conclusively that the Mackinac Bridge, as designed, has:

1. Complete and absolute stability against *vertical* oscillations at all wind velocities and all angles of attack.
2. Complete and absolute stability against *torsional* oscillations at all wind velocities and all angles of attack.
3. Complete and absolute stability against *coupled* oscillations (combining vertical and torsional) at all wind velocities and all angles of attack.

Professor Farquharson also tested the Mackinac Bridge model with all roadway and sidewalk grids closed solid, to represent the hypothetical, abnormal condition of all openings completely closed by ice.

For the normal condition, with the grids open, as recorded above, the Mackinac Bridge section has been proved to have perfect aerodynamic stability.

*For the abnormal condition*, with all grids completely closed by ice,

the aerodynamic stability is found to be *so nearly perfect that the difference is practically meaningless.*

The Mackinac Bridge will have an exceptionally high value of *structural damping* (resisting any tendency to start oscillations). The high vertical rigidity and the still higher torsional stiffness contribute this high value of the structural damping. The magnitude of the structural damping factor or logarithmic decrement will certainly be at least 0.05. Professor Farquharson has estimated for the Mackinac Bridge a structural damping factor of approximately 0.08. For the abnormal condition of all deck openings completely closed by ice and snow, the action of the interlocked ice and the packed snow will contribute further to the structural damping, and for this condition the structural damping may be estimated as 0.10.

For a minimum assumed value of 0.05 for the structural damping, the wind-tunnel tests for the bridge with the deck completely closed show complete and absolute stability against *vertical* oscillations at *all* wind velocities; complete and absolute stability against *torsional* oscillations at *all* wind velocities; and complete and absolute stability against *coupled* oscillations at all wind velocities up to a wind velocity of 524 miles per hour for the lowest mode of oscillations, 779 miles per hour for the next mode, and 800 miles per hour for the next higher mode.

For the higher and more probable estimated value of 0.10 for the structural damping, the wind-tunnel tests for the bridge with the deck completely closed (as by ice) show complete and absolute stability against *vertical* oscillations at *all* wind velocities; complete and absolute stability against *torsional* oscillations at *all* wind velocities; and complete and absolute stability against *coupled* oscillations *at all wind velocities up to a wind velocity of 632 miles per hour for the lowest mode of oscillations, 942 miles per hour for the next mode of oscillations, and 966 miles per hour for the next higher mode of oscillations.*

Accordingly, even under the worst abnormal conditions, the Mackinac Bridge is *ultra-safe against any possibility of aerodynamic oscillations.* The indicated critical velocities (for the assumed abnormal conditions) approach the supersonic range.

The highest wind velocity ever recorded in the vicinity of Mackinac is 78 miles per hour. The required "critical velocities" of 632, 942, and 966 miles per hour may be dismissed as fantastically impossible.

### COMPARISON WITH PRIOR SUSPENSION BRIDGES

The outstanding superior aerodynamic stability achieved in the Mackinac Bridge is best shown by a comparison (Table III) with the critical velocities determined by similar wind-tunnel investigations for other notable suspension bridges.

For the prior long-span bridges, the critical wind velocities listed in the following tabulation are taken from published reports by Professor

F. B. Farquharson in official Bulletins (1954) of the University of Washington Engineering Experiment Station.

TABLE III.

| Bridge | Critical Wind Velocity mph. |
|---|---|
| Bronx-Whitestone (after addition of stiffening trusses) | 30 |
| Golden Gate | 40 |
| George Washington | 55 |
| New Tacoma Narrows | 76 |
| *Mackinac* (with deck closed) | *632* |
| *Mackinac* (with deck open, as designed) | *Infinite* |

The methods developed and applied for predetermining a design of assured aerodynamic safety constitute the key to the future design of suspension bridges for aerodynamic stability.

## CONCLUSION

The Mackinac Bridge is one hundred per cent safe, aerodynamically, even under the most adverse conditions that may be expected to occur.

The Mackinac Bridge represents the achievement of a new goal of perfect aerodynamic stability, never before attained or approximated in any prior suspension bridge design.

# RESEARCHES ON CORROSION AND INHIBITION

## REACTION VELOCITY IN THE SYSTEM IRON: DILUTE ACETIC ACID AT 40° C.

BY

GEORGE S. GARDNER,[1] HARRY L. FAIGEN,[1] GREGORY L. GIBSON [1] AND WILBUR S. HALL [1]

Part II [2]

### CALCULATION OF REACTION VELOCITY CONSTANTS AND FRACTIONAL SURFACE COVERED

If we let

$M$ = molecular weight of reactant (acetic acid),
$x$ = milligrams of reactant in the solution at time $t$,
$x_0$ = milligrams of reactant in the solution at time $t = 0$,
$t$ = time in hours, measured from the beginning of the experiment,
$A$ = area of the metal surface, cm.$^2$,
$V$ = volume of the aqueous phase, cm.$^3$,
$w$ = weight loss of the metal surface at time $t$, in mg.,

then $x/1000M = m$ = moles of reactant in the solution at time $t$. Substituting in (5),

$$-dx/x = (1 - s)(AD/hV)dt \tag{7}$$

and, integrating,

$$-\ln x = (1 - s)(AD/hV)t + \text{constant.}$$

Since $x = x_0$, when $t = 0$, the integration constant is $-\ln x_0$, and

$$\ln (x_0/x) = (1 - s)(AD/hV)t \tag{8}$$

or

$$(1 - s)AD/hV = \ln (x_0/x)/t. \tag{9}$$

Here, then, is a means of determining the group $(1 - s)AD/hV$. If we plot values of $\ln (x_0/x)$ as ordinates, against values of the time, $t$, as abscissa, the slope is the group $(1 - s)AD/hV$. Although the value of $x$, the number of milligrams of reactant in the solution at time $t$, has not been determined directly, it can be determined from the weight of iron dissolved, as follows:

[1] The Research Laboratories of The American Chemical Paint Co., Ambler, Pa.
[2] Part I appeared in this JOURNAL for November, 1956.

*a. For 30 ml. of brine and 30 ml. of mineral spirits*

Since the glacial acetic acid used corresponded to 1000 ppm. by volume, each 30 ml. of brine contained 31.5 mg. of acetic acid, and $x_0 = 31.5$. The conversion of $w$, the mg. of iron dissolved in time $t$, to $(x_0 - x)$, the mg. of acetic acid used up at time $t$, is given by

$$(x_0 - x) = (120/55.85)w = 2.15\ w,$$

and

$$x = 31.5 - (2.15\ w). \tag{10}$$

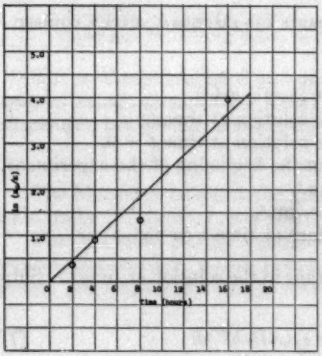



FIG. 5.

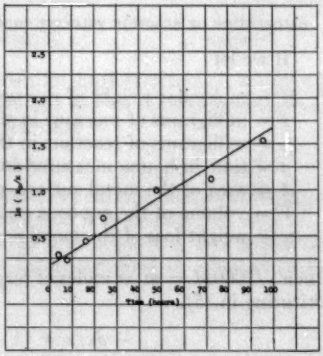



FIG. 6.

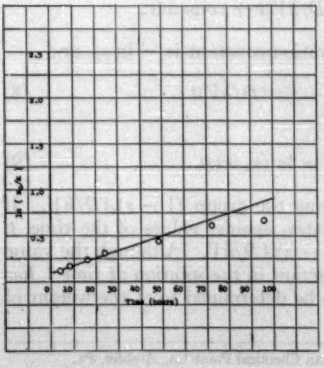



FIG. 7.

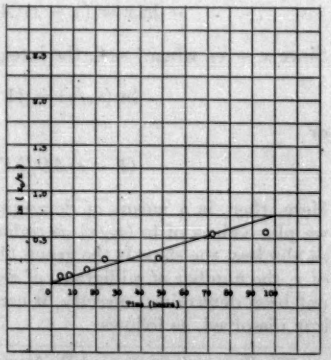



FIG. 8.

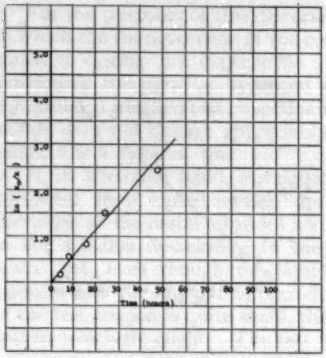



FIG. 9.

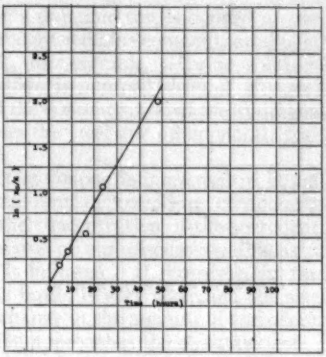



FIG. 10.

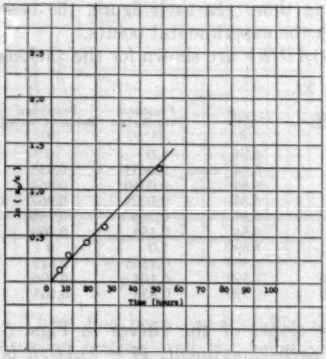



FIG. 11.

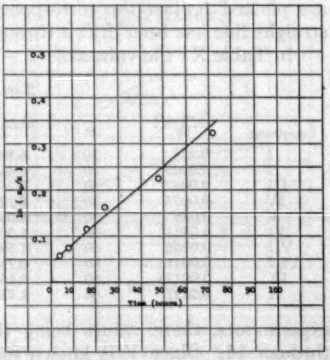



FIG. 12.

*b. For 60 ml. of brine, and no mineral spirits*

Here, for 1000 ppm. of acetic acid by volume, $x_0$ is 63.0, in terms of mg. of acetic acid. Also,

$$x = 63.0 - (2.15\,w). \tag{11}$$

Tables I through X give all the data necessary for the calculation of the values of ln $(x_0/x)$, and, in the last column of each table, these values are calculated for each value of the time.

In Figs. 5 through 14, the values of ln $(x_0/x)$ for each experiment

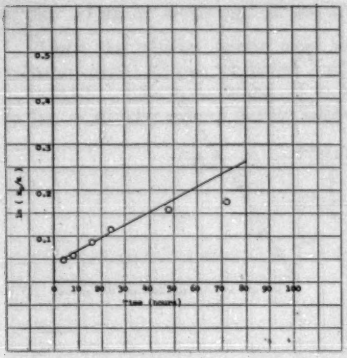



FIG. 13.

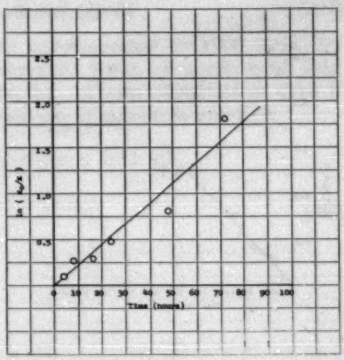



FIG. 14.

are plotted against the corresponding time. In each figure, the best straight line has been drawn through the experimental points.

In Table XI the values of $(1 - s)AD/hV$ are shown for the various

TABLE XI.

| Experiment | $\frac{(1-s)AD}{hV}$ | $V$ | $\frac{(1-s)AD}{h}$ | $\frac{AD}{h}$ | Fractional Free Surface $(1-s)$ | Fractional Surface Covered $(s)$ |
|---|---|---|---|---|---|---|
| I | 0.228 | 30 | 6.84 | 6.84 | 1.0 | 0 |
| II | 0.0149 | 30 | 0.447 | 6.84 | 0.0653 | 0.935 |
| III | 0.0082 | 30 | 0.246 | 6.84 | 0.0360 | 0.964 |
| IV | 0.0075 | 30 | 0.225 | 6.84 | 0.0329 | 0.967 |
| V | 0.056 | 30 | 1.680 | 6.84 | 0.246 | 0.754 |
| VI | 0.0434 | 30 | 1.302 | 6.84 | 0.191 | 0.809 |
| VII | 0.0265 | 60 | 1.590 | 1.590 | 1.0 | 0 |
| VIII | 0.00415 | 60 | 0.249 | 1.590 | 0.1565 | 0.843 |
| IX | 0.00276 | 60 | 0.1656 | 1.590 | 0.104 | 0.896 |
| X | 0.0221 | 60 | 1.3260 | 1.590 | 0.835 | 0.165 |

experiments, these values being the slopes of the curves in Figs. 5 through 14. Since $V$ is known for each experiment, $(1 - s)AD/h$ is obtained by multiplying these slopes by $V$. Since two of the experiments, I and VII, have been made in the absence of added inhibitor, the surface covered by inhibitor $s$ is zero, and the free surface $(1 - s)$ is 1.0. The values of $AD/h$ are thus calculated, and are shown in the table. Having the values of $AD/h$, the values of $(1 - s)$ are easily calculated, and are shown in the table for the various experiments, together with the values of $s$.

## APPLICATIONS TO THE EVALUATION OF CORROSION INHIBITORS

While there are many methods used for making corrosion tests and for evaluating corrosion inhibitors, all the procedures can be classified under one or the other of two headings: *dynamic* or *static*.

For the purposes of this discussion a dynamic test is defined as one in which the concentration of the corrodent remains constant, or almost constant during the experiment. If, for example, a brine solution containing 500 ppm. of hydrogen sulfide is pumped through a vessel containing a weighed test coupon, and the concentration of the hydrogen sulfide does not change appreciably as the steel (or other metal) corrodes, it is a dynamic test.

If, on the other hand, a weighed test coupon is immersed in liquid corrodent in a closed vessel, the amount of corroding component decreases as the metal corrodes and the concentration of the corrodent in the solution decreases. In the sense of our discussion, this is a static test, even though the liquid is agitated. If, however, in the closed vessel the amount of corroding liquid is very large and the size of the test coupon is quite small, the change in the amount of corrodent will be relatively slight. The test then approaches the dynamic test.

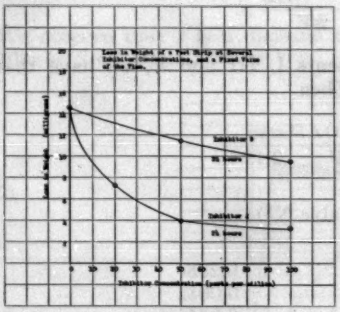


FIG. 15.

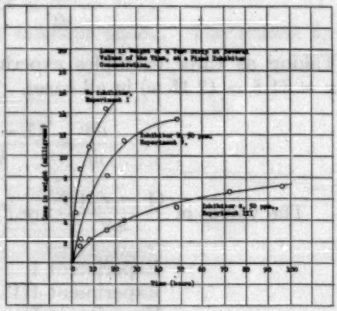


FIG. 16.

There has been considerable adverse criticism directed at static corrosion testing, and the belief persists that the results yielded by static testing are relatively imperfect, as compared to the results of dynamic tests. Careful consideration of this question, however, will reveal that the reaction velocities involved must be the same in each procedure, and that any divergence in results must come from improper analysis of the data, or from incomplete data, and not from any basic difference in mechanism.

In Fig. 15 are shown the results of static corrosion tests on two corrosion inhibitors. In fact, they are experiments III and V described above. In these tests the weighed metal strip was agitated in the corrodent (1000 ppm. acetic acid at 40°C.) for a fixed time (24 hr.). Each point shows the loss in weight for a definite inhibitor concentration. While we readily believe that *A* is a better inhibitor than *B* under

these conditions, the degree to which it is better is not readily apparent, since in the various tests different amounts of initial corrodent have been used up in the 24-hr. period, and therefore the tests have not been run under equivalent conditions.

Figure 16 shows another way in which this corrosion test was made. Now the inhibitors have been compared at one concentration (50 ppm.), but measurements have been made, in separate experiments (see Tables III and V), at various values of the time. One result is immediately apparent: since time is a variable in the results of Fig. 16, over-all corrosion velocity can be calculated (see data already given). This is not the case, however, with the data of Fig. 15, since the time is not a variable.

To show what can be done with the data of Fig. 16, consider the following: Rewriting Eq. 7,

$$-\frac{dx}{dt} = \frac{(1-s)AD}{hV}x.$$

Taking as three examples experiments I, III and V, we have that $x = 31.5 - (2.15\,w)$ in all cases. Then

$$\frac{dw}{dt} = \frac{(1-s)AD}{hV}\frac{x}{2.15}.$$

The values of $\frac{(1-s)AD}{hV}$ are (Table XI):

| | |
|---|---|
| Experiment I | 0.228 |
| Experiment III | 0.0082 |
| Experiment V | 0.056. |

Now, for all these experiments, $x = 31.5$ at $t = 0$.
The values of $dw/dt$, at $t = 0$, are therefore

| | |
|---|---|
| Experiment I | 3.33 |
| Experiment III | 0.120 |
| Experiment V | 0.818. |

In other words, we now know the initial slope—the slope of the curve if the experiment was made under dynamic conditions—the slope of the curve when the concentration of corrodent is constant. The results of a static experiment can thus be converted to a dynamic curve if sufficient data are available. This has been done in Fig. 17 for the three experiments.

### 2. THE FRACTIONAL SURFACE COVERED: A USEFUL INHIBITOR FUNCTION

The theory that corrosion inhibitors act by adsorption on metal surfaces has had quite general acceptance, regardless of the fact that investigators differ on the exact mechanism. It appears reasonable, then, that the fractional surface covered by adsorbed inhibitor should be a direct measure of inhibition, as, in fact it is in this paper, since the fractional surface covered was actually calculated from inhibition data. This function $s$ offers us, then, in the form of a single function, the actual value of a corrosion inhibitor under a given set of conditions. Again comparing inhibitors $A$ and $B$, we show the following:

TABLE XII.

| Experiment | Inhibitor | $(1-s)$ | $(s)$ | $S=100s$ |
|---|---|---|---|---|
| III | $A$, 50 ppm. | 0.0360 | 0.964 | 96.4 |
| IV | $A$, 100 ppm. | 0.0329 | 0.967 | 96.7 |
| V | $B$, 50 ppm. | 0.246 | 0.754 | 75.4 |
| VI | $B$, 100 ppm. | 0.191 | 0.809 | 80.9 |

We observe that $s$ is a measure of *inhibitor action*. The reason for $100s = S$ will appear below.

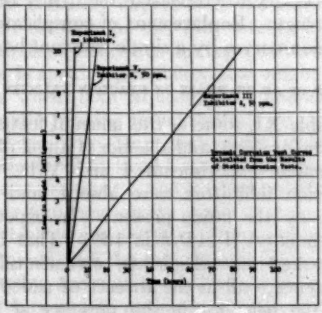


FIG. 17.

### A NEW PROCEDURE FOR THE EVALUATION OF CORROSION INHIBITORS

Here is a procedure we suggest for corrosion testing, which, in our opinion, will give a true comparison of corrosion inhibitors under acidic corrosion conditions. The method can no doubt be applied to the study of many types of corrodents.

1. The total corrodent in the solution should be known. From this the value of $x_0$ is obtained.

2. In the absence of inhibitor, values for the loss in weight at several values of the time should be obtained. These are the values of $w$, from which the values of $x$ can be calculated.

3. From these data, a table similar to Table I can be constructed, and a curve similar to (I) can be drawn.

4. The slope of this curve gives $(1 - s)AD/hV$, and since $(1 - s)$ is 1.0, when no inhibitor is present, and $V$ is known, $AD/h$ is readily calculated.

5. Now, in the presence of a known concentration of inhibitor, similar loss in weight data are obtained at several values of the time.

6. A table similar to II can then be constructed, and a curve similar to II can be drawn.

7. Again we obtain from the curve the slope, which is $(1 - s)AD/hV$. In this quantity, now, $AD/hV$ is known, and $(1 - s)$ can be calculated.

The value of $(1 - s)$ so obtained, can be used in one of several ways. One very useful way might be to use it as the basis for calculation of a standard constant of inhibition, to hold for a given set of conditions. Such a constant might be $100s$, which we might designate as $S$. (See Table XII).

It is hardly necessary to emphasize the utility of such a procedure in corrosion technology. Replacement of complicated, and frequently meaningless corrosion curves by a single constant has much to offer.

### THE INFLUENCE OF AN OIL PHASE ON REACTION VELOCITY EXPERIMENTS

If we study Table XI, some of the unusual features of the relative corrosion rates in the presence and absence of an oil phase come to light. Consider, for example, experiments I and VII. In both of these experiments corrosion inhibitors were absent, and the reactions are controlled entirely by the fluids present. In experiment I $AD/h$ is 6.84, and in experiment VII $AD/h$ is 1.59. That is, in the presence of the oil phase (washed mineral spirits), corrosion takes place 4.3 times as fast as in its absence,—all in the absence of added inhibitor.

Now consider the behavior in the presence of inhibitors. If we consider experiments II and VIII, in each of which 20 ppm. of inhibitor $A$ was used, we note a value of $s$ with mineral spirits of 0.935, and a value of $s$ without mineral spirits of 0.843. Again, with the same inhibitor, $A$, at a concentration of 50 ppm., in experiments III and IX, the value of $s$ with mineral spirits is 0.964 and the value without mineral spirits is 0.896. Also, in experiments $V$ and $X$, on inhibitor $B$, at a concentration of 50 ppm., the values of $s$ are 0.754 with mineral spirits and 0.165 without mineral spirits.

There are some investigators in the field of oil well corrosion who believe that the value of a corrosion inhibitor is directly related to its ability to alter the surface tension relations between oil, water or brine,

and steel, in such a way as to permit the oil to wet the steel preferentially, and thus protect the steel from corrosion. Others believe that it is the inhibitor, *per se*, through its adsorption on the steel surface, that protects the steel, and the strength of the inhibitor depends on the strength of the adsorption bonds and the amount of surface covered by this adsorption.

The results shown in Table XI offer interesting support to both theories, and show that some inhibitors are strongly adsorptive, and that other inhibitors tend to be water displacing. For example, the results of experiments II, III, IV, VIII, and IX indicate that inhibitor *A*, although slightly weaker in the absence of mineral spirits, is nevertheless an exceptionally efficient inhibitor under both sets of conditions. Experiments V, VI, and X show quite different results for inhibitor *B*. In the presence of mineral spirits this inhibitor is moderately effective. In the absence of mineral spirits, however, its effectiveness is almost nil.

Earlier in this paper we brought up some questions about the reaction velocity of corrosion as affected by the presence or absence of oil phases. This discussion can now be continued in the light of the foregoing experiments:

While we would certainly expect that the rate of diffusion of an aqueous component through an oily film would be very much slower than through an aqueous film, thus having a definite tendency to slow the reaction, there is another possibility that might work in quite the opposite direction when both aqueous and non-aqueous phases are present. In a rapidly moving liquid system we think of an aqueous film as scouring the surface, thus profoundly affecting the thickness of any aqueous films. Why could not an oil phase have a definite scouring effect on a water film? And is it not possible that an oil phase could scour a water film, and at the same time not replace the water film with a film which is protective? The experiments reported here are not sufficient to establish the fact that such a condition exists; it is, however, an interesting speculation, and would bear more experimentation, since it could very well be an important factor in oil well corrosion.

Neither do the experiments permit us to say that corrosion in water-oil systems is accelerated by the creation of greater potential differences between various areas. The same is true of the question of the effect of oil on hydrogen polarization.

### ADDITIONAL WORK PLANNED

The experiments carried out to date on the corrosion reaction between iron and acetic acid do not show definitely that the reaction is diffusion-controlled. As pointed out earlier in this paper, the following additional experiments are necessary to answer this question: (1) experiments at several values of the agitation rate; (2) experiments at another temperature; and (3) experiments on different types

of metal. Work along these lines is continuing in this laboratory. In addition to these experiments, we are carrying out considerable work on the influence of various types of oil phases on corrosion reaction velocity, and related inhibitor effects. It is our hope that the results of this investigation, and the work which is planned to follow it, will shed some light on the extremely complex series of reactions we know as "corrosion reactions."

*Acknowledgments*

We wish to express our appreciation to Alfred Douty, Technical Director of the American Chemical Paint Company, and the staff of the Research Laboratory, for intelligent assistance and advice during the progress of this work, and particularly to John Waldrum for skillful design and construction of the mechanical equipment.

## NOTES FROM THE NATIONAL BUREAU OF STANDARDS

### CONTROLLING CONDUCTIVITY IN SILICATES

An urgent need for high-temperature electrical insulating materials has led the National Bureau of Standards to investigate methods of decreasing conduction in the basic glasses or frits used in vitreous ceramic coatings.[1] Results of the study indicate the general type of composition yielding coatings of high resistance. A better understanding of the basic mechanisms controlling electrical conduction in glasses has also resulted from the project, which was sponsored by the Office of Ordnance Research, Department of the Army. S. W. Strauss, D. G. Moore, W. N. Harrison, and L. E. Richards of the Bureau's enameled metals laboratory conducted the investigation. The research was aimed indirectly at producing ceramic-coated parts having "built-in" electrical resistance superior to that of mica.

Conductivity in vitreous silicates at high temperatures is generally thought to be the result of the net unidirectional migration of alkali ions through the interstitial holes of the silicate framework. For an ion to migrate, its free energy of activation must be exceeded. That is, sufficient energy must be supplied to break the chemical bond between the alkali ion and the oxygen, and to move the ion to the next interstitial position. Thus, the conduction process may be pictured as a series of migrations of conducting ions from interstice to interstice. To obtain a better insight into the conduction mechanism, the Bureau made a detailed study of the conductivity of simple glass-forming systems, including a large number of ternary lead silicates and lithium sodium silicates.

Specimens were prepared for test by spraying a thin layer of silver paint onto each face. Stainless steel electrodes, located within the heating core of a furnace, were placed in contact with the specimen and the furnace was heated at the rate of about 10°C. per minute. Voltage from a 200-v dry cell was applied during the entire heating period, polarity being reversed at least once each 20°C., and current was measured at 10° C. intervals. The resistances of the glasses were determined from the current, voltage, and dimensions of the specimens for temperatures up to 500°C. in some cases.

[1] For further technical details see: "Fundamental Factors Controlling Electrical Resistivity in Vitreous Ternary Lead Silicates," by S. W. Strauss, D. G. Moore, W. N. Harrison, and L. E. Richards, *J. Research NBS*, Vol. 56, p. 135 (1956) RP 2658; "Electrical Resistivity of Vitreous Ternary Lithium Sodium Silicates," by S. W. Strauss, *J. Research NBS*, Vol. 56, p. 183 (1956) RP 2665; "Effect of Temperature on the Electrical Resistivity of Several Ceramic and Silicone Type Coatings," by S. W. Strauss, D. G. Moore, and L. E. Richards, ASTM sp. Tech. Publ. No. 153, 101–8 (1953).

The observed variation in resistivity with change in composition indicates that conductivity depends on the nature of ions, being affected by such factors as their size and charge. Relationships between resistivity, composition, bonding energy, and experimental heat of activation of ternary lead silicates suggest that alkali ions may be the only conducting ions. Traces of alkali ions appear to decrease electrical resistivity, making purity of materials a main consideration in preparing alkali-free high-resistivity ceramic coatings. However, when the fusion point of the frit is very high, it may be necessary to add alkali ions to obtain workable coatings.

For lithium sodium silicates, a correlation was revealed between resistivity and composition, and between experimental heat of activation and composition. This finding indicates that substitution of two alkali ions for the same mole per cent of either one leads to a more compact structure which decreases ionic migration. Thus, a composition containing approximately equimolar quantities of lithium oxide and sodium oxide has the most compact structure, and therefore the highest resistivity, in the ternary lithium sodium silicate system.

The investigation leaves some questions unanswered, such as whether or not hydrogen ions from water in the glass contribute to conduction. However, the study represents a definite contribution to the conduction theory and provides data that should be helpful in the design of glasses, glazes, and ceramic coatings of specified resistivities.

## MOTION PICTURES OF METAL FATIGUE

The National Bureau of Standards has recently constructed a small fatigue-testing machine equipped with a motion picture camera for filming the microscopic features of a metal surface during fatigue fracture. Designed by J. G. Weinberg of the Bureau's mechanical metallurgy laboratory, the apparatus uses a clock-controlled, 16-mm. camera to take time-lapse motion pictures of aluminum specimens under torsional stress.

An understanding of fatigue phenomena is important to the engineer in predicting the life of a metal in service and to the metallugist in designing more fatigue-resistant metals. In order to obtain detailed information on fatigue for use in aircraft design, the National Advisory Committee for Aeronautics is sponsoring a Bureau study of the basic factors influencing fatigue crack initiation. The films made in the course of this investigation should simplify tedious laboratory determinations by providing automatically recorded, detailed pictures of the fatigue process.

The base of the fatigue-testing machine is a block of steel designed to fit the stage of a metallurgical microscope. The base is machined at the top to a shallow U-shape, and a horizontal collet for holding the test specimen is inserted through the upper parts of the block. Two small

eccentric cams are mounted at the ends of a motor-driven shaft passing through the lower part of the base so that cam followers can transmit the load to the ends of the collet above. The metal specimen to be filmed is pressed into the collet, and an alternating torsional load is applied through the cam followers by the cams, which are mounted 180° out of phase. The amount of load is determined by the degree of cam eccentricity. An 0.01-in. hole, drilled in the top surface of the specimen, provides a focusing target for the microscope. Any fatigue failure that occurs will tend to develop around the hole and thus be in the field of the microscope.

The camera is attached to the principal eyepiece of the microscope while a second eyepiece permits simultaneous visual observation. A large disc with a hole near its edge revolves on the motor shaft and serves as a shutter by interrupting the light to the microscope's vertical illuminator. This arrangement permits successive exposures at the same point of the stress cycle. It is necessary because each frame may be exposed a number of times before another takes its place.

The film is advanced at regular intervals by a synchronous motor-driven cam that actuates the camera's single frame button, the camera shutter being adjusted to close only during film transport. Since the speed of the fatigue machine can be adjusted with respect to the movement of the film, the number of stress cycles per frame can be varied depending on how rapidly changes are taking place in the metal surface.

Portions of the films taken during the early stages of the fatigue test showed no unexpected changes. Slip bands developed in the highly stressed regions around the hole, and these gradually became more numerous and heavier until some of them developed into cracks. During the latter stages of the test a crack developed in an area that had contained no slip bands in the early part of the test. A short time later material began to be extruded from this opening at irregular intervals, but in surprisingly large quantities considering the size of the crack. Since the crack was only 0.01 in. long and the extruded ribbon very thin, the actual amount of material driven out was extremely small. This phenomenon occurred suddenly and was not observed until the film was developed and viewed, so that no attempt could be made to collect the extrusion for chemical analysis. However, it has been suggested that the extruded material, if not an oxide of some kind, is so fine that it probably reacts immediately with the atmosphere to form one.

## COMPUTING DEVICE FOR WATER CONTENT OF GASES

A simple hand computer for rapidly calculating the water content of gases has been developed by A. W. Diniak and E. R. Weaver of the National Bureau of Standards. Of the circular slide-rule type, the new

computer[1] is faster, more accurate, and less expensive than previous devices for this purpose. In connection with the Bureau's method[2] for determining moisture in gases, the computer has been used by the armed services to calculate the water content of aviator's oxygen, rocket fuels, and fire-extinguisher gases. The device should also save considerable time in such industrial applications as the determination of refrigerating system characteristics and control of moisture in inert and reducing gases.

The computer is designed primarily to calculate water content and dew-point of gases from observations of the electrical conduction of a hygroscopic film as it absorbs water vapor. Corrections are automatically made for deviations from the ideal laws relating to vapors in gases. Such deviations are independent of measurement methods but nevertheless affect computations in which they have usually been ignored.

The computer consists of a plastic base disc about 4 in. in diameter and two smaller rotating discs marked with appropriate temperature, pressure, and altitude scales. Additional scales may be read through a plastic window in the top disc, thus extending the scope and improving the readability of the device. A logarithmic scale on the rim of the base disc resembles that of an ordinary slide-rule and may be used for a number of computations involving conversion from one unit to another.

[1] For further technical details, see "A New Computer for Calculating the Water Content of Gases," by A. W. Diniak, and E. R. Weaver, *J. Research NBS*, Vol. 56, p. 269 (1956) RP 2674.

[2] See "Measurement of Water in Gases by Electrical Conduction in a Film of Hygroscopic Material and Use of Pressure Changes in Calibration," by E. R. Weaver and R. Riley, *J. Research NBS*, Vol. 40, p. 169 (1948) RP 1865; also "Moisture Determination by Electrolytic Film," *NBS Tech. News Bull.*, Vol. 32, p. 13 (February 1948).

## MEDAL DAY PROCEEDINGS AT THE FRANKLIN INSTITUTE

### October 17, 1956

### RECEPTION AND DINNER

On Wednesday, October 17, 1956, approximately 275 Institute members and guests gathered to pay tribute to the men whose achievements had been recognized by the Committee on Science and the Arts during the past year. A reception honoring the 1956 Medalists was held at 6:30 P.M. in the lobby of Franklin Hall, and at 7:10, the guests assembled for dinner in the Hall. Mr. Robert G. LeTourneau, the 1956 Frank P. Brown Medalist and a lay preacher, asked the blessing.

During dinner, Mr. S. Wyman Rolph, President of the Institute, thanked the members of the Hostess Committee for their assistance at the reception and for the floral decorations. Mr. Rolph proposed toasts to Benjamin Franklin and to Her Majesty Queen Elizabeth II; Her British Majesty's Consul General, Mr. Geoffrey W. Aldington, offered a toast to the President of the United States.

Mr. Francis B. Foley, Chairman of the Committee on Science and the Arts, introduced the following former Medalists who were present at the dinner.

FORMER MEDALISTS ATTENDING MEDAL DAY—1956

| Year | Medalist | City |
|---|---|---|
| | CRESSON (1848) | |
| 1904 | G. H. Clamer | Philadelphia, Pa. |
| 1938 | Edwin H. Land | Cambridge, Mass. |
| | CERTIFICATE OF MERIT (1882) | |
| 1902 | Myron Francis Hill | Westport, Conn. |
| 1921 | Joseph S. Hepburn | Philadelphia, Pa. |
| 1942 | Walter Larkin | Philadelphia, Pa. |
| 1944 | Western Union<br>Represented by: H. P. Corwith | New York, N. Y. |
| 1945 | Walter J. Coppock | Moylan, Pa. |
| 1946 | Ronald D. Dodge | Poughkeepsie, N. Y. |
| | LONGSTRETH (1890) | |
| 1909 | J. H. Granbery | New York, N. Y. |
| 1911 | Joseph S. Hepburn | Philadelphia, Pa. |
| 1921 | L. H. Adams | Washington, D. C. |
| 1921 | W. Barton Eddison | Ardsley-on-Hudson, N. Y. |
| 1922 | Joseph F. Keller | New York, N. Y. |
| 1923 | Harry S. Parks | Pottstown, Pa. |
| 1927 | James F. Smathers | Poughkeepsie, N. Y. |
| 1936 | Elmer A. Sperry | Wilton, Conn. |
| 1947 | Samuel Berman | Ozone Park, N. Y. |
| 1948 | Nicholas F. Arone | Upper Darby, Pa. |

POTTS (1906)

| | | |
|---|---|---|
| 1947 | Robert H. Kent | Havre de Grace, Md. |

LEVY (1923)

| | | |
|---|---|---|
| 1938 | Alger L. Ward | Bala Cynwyd, Pa. |
| 1946 | George S. Southworth | Chatham, N. J. |

WETHERILL (1925)

| | | |
|---|---|---|
| 1941 | Harold S. Black | Summit, N. J. |
| 1949 | Harlan D. Fowler | Longmont, Colo. |

BROWN (1938)

| | | |
|---|---|---|
| 1947 | Karl P. Billner | Philadelphia, Pa. |
| 1955 | Charles S. Leopold | Philadelphia, Pa. |

BALLANTINE (1946)

| | | |
|---|---|---|
| 1947 | George C. Southworth | Chatham, N. J. |
| 1948 | Ray D. Kell | Princeton, N. J. |
| 1953 | David G. C. Luck | Bryn Mawr, Pa. |

## CEREMONIES IN THE LECTURE HALL

At the conclusion of dinner, the guests assembled in the Lecture Hall, where Mr. Rolph presided over the Stated October Meeting[1] of the Institute and the presentation of awards. Dr. John S. Burlew, Executive Vice President of the Institute, was asked to report on "Coming Events at the Institute."

### REPORT OF THE EXECUTIVE VICE PRESIDENT

"Our principal interest at Medal Day is to look back and survey the noteworthy achievements of the medalists. Before we reach that part of the program I should like to take a few minutes to look ahead at some of the Coming Events at The Institute.

"The first in a new series of events took place a week ago. This was an open house evening at the Museum, sponsored by some of our principal Museum exhibitors: Bell Telephone Company, Bethlehem Steel Company, Budd Company, Curtis Publishing Company, and Sun Oil Company. The guests on that occasion were some 215 members of Rotary Clubs in Philadelphia and neighboring communities. It is planned to invite other groups from time to time this winter, so that an increasing number of adults will become aware of the unique value of The Franklin Institute Museum to the community.

"As part of the Institute's educational activities we are searching for additional ways in which we can help alleviate the serious national shortage of scientists and engineers. The regularly scheduled visits of school children to the Museum of course can be expected to have some beneficial influence. About a year and a half ago we took an additional positive step. With the cooperation of the American Society for Metals we staged a career forum concerning metallurgy, aimed to interest high school students in that subject as a possible career. That first suc-

[1] The minutes of this meeting were printed in this JOURNAL for November, 1956, p. 399.

cessful forum was followed by one in electronics last year, staged with the help of the Institute of Radio Engineers and several local electronics companies. Now we are planning similar forums for chemistry on November 14 and April 12, in cooperation with the Philadelphia Section of the American Chemical Society. If you know a boy or girl who has shown some interest in chemistry, be sure to have him or her attend one of these sessions, which will dramatize the possible careers in the profession of chemistry.

"Among many lectures held here at The Franklin Institute there is an informal series known as 'Science is Fun.' At each of these meetings we try to show to our members and their guests some interesting application of science described by an expert in the field, who has the knack of making his subject understandable to non-scientists. The next Science is Fun meeting will be on December 12, at which Mr. Homer Jensen of the Aero Service Corporation of Philadelphia will tell about aerial exploration.

"The Institute's Laboratories for Research and Development continue to perform basic and applied research for industry and for government; and in fact this year 1956 will see the total value of this work exceed three million dollars for the first time. We can publicize very few of the results, because of the requirements of secrecy, either for military security or to protect the competitive position of an industrial sponsor.

"Occasionally, however, the Laboratories are able to hold public discussions of their work. Two days ago, a symposium was devoted to the subject of air pollution. This is a field of work in which the Laboratories have made a widely recognized contribution. Another in the near future will be a two-day symposium on the subject of automatic programming for digital computers. This is a subject that has been pursued successfully by the Analysis Section of the Laboratories for several years. The symposium not only will give us an opportunity to acquaint others with these results, but also it will signal the opening of the Institute's Univac Computing Center, which will be available to industry for the solution of engineering problems and others requiring extensive computation.

"The installation of the Univac computer is important to the Institute in another way. It will form the focal point of a new exhibit on computation that is being installed by the Remington-Rand Division of the Sperry Rand Corporation, the makers of Univac. We hope to have the exhibit, including the Computing Center, ready for display early in February. In conjunction with the opening you will be pleased to know that we plan to have a preview for members of the Institute.

"These, then, are a few highlights of the coming fall and winter season here at The Franklin Institute. I hope that you will tell your friends, so that they will accompany you as you return to enjoy at least some of these coming events."

## PRESENTATION OF AWARDS

Mr. Rolph then paid tribute to the Committee on Science and the Arts, in these words:

"Before proceeding with the formal presentation of the Medals, it seems appropriate that thanks be extended not only to the Sponsors of the 1956 Medalists but to all of the members of the Committee on Science and the Arts who have made these awards possible. These Committee members spend many hours in meetings of the Committee as well as countless hours of their own time in pursuing their conscientious and thorough investigations of each subject brought to their attention, and in order to maintain the splendid tradition of this unique group which was formed when the Institute was founded with Alexander Dallas Bache, great grandson of Benjamin Franklin, as its first Chairman. I remind you that this group was organized one hundred and thirty-two years ago.

"Each Medalist is sponsored by the chairman of the sub-committee of the Committee on Science and the Arts which recommended him for the award. This Sponsor will present the Medalist and read his citation."

### PRESENTATION OF THE EDWARD LONGSTRETH MEDAL
(Founded in 1890)

This Medal is awarded for inventions of high order and for particularly meritorious improvements and developments in machines and mechanical processes.

*To Floyd A. Firestone, Physicist, Dobbs Ferry, New York.*

MR. ROLPH: "The Chair recognizes Dr. Raymond C. Machler."

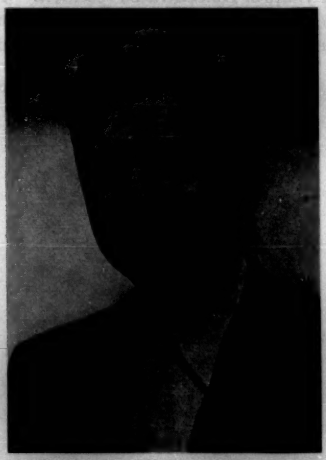
DR. MACHLER: "Mr. President, I present Floyd A. Firestone for an award.

"Dr. Firestone invented the first practical ultrasonic test equipment for the detection of flaws in metals. The simplest form of this equipment uses a quartz crystal to generate an ultrasonic pulse. The pulse can travel through many feet of metal and is partially reflected by defects in the path of the beam, as well as by the other end of the metal piece. The various reflections are detected by the same crystal and are presented on a cathode ray tube along with a suitable time or distance scale so that the operator can estimate the size of the defect and measure its location within the test piece.

"Equipment for ultrasonic flaw detection has found extensive use in the inspection of large rotating shafts and other metal parts in which the ultimate in reliability is required.

"The invention has been recognized as providing the only means for the routine inspection for fatigue cracks in long, heavy shafts such as are used in steam turbines, and so forth.

"The more extensive use of the invention is in the control of quality of materials. The existence of this equipment commercially has led to substantial improvement in the quality of large forgings and critical castings.



FLOYD A. FIRESTONE

"I present Floyd A. Firestone, of New York, New York, as a candidate for an Edward Longstreth Medal, 'For his invention and development of a practical industrial tool for the detection and measurement of the location and extent of defects in metal parts by ultrasonic means.' "

MR. ROLPH: "Dr. Firestone, by reason of my office as President of The Franklin Institute of the State of Pennsylvania, I present to you this Edward Longstreth Medal and the Certificate and Report which accompany it."

**PRESENTATION OF THE HOWARD N. POTTS MEDAL**
**(Founded in 1906)**

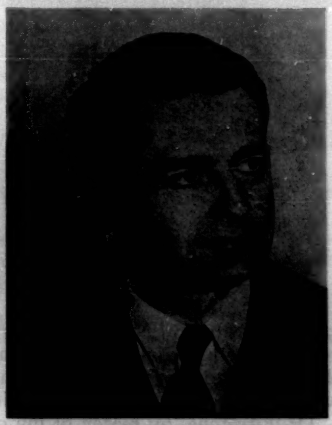
This Medal is awarded for distinguished work in science or the arts; important development of previous basic discoveries; inventions or products of superior excellence or utilizing important principles.

*To Edwin H. Land, President and Director of Research, Polaroid Corporation, Cambridge, Massachusetts.*

MR. ROLPH: "The Chair recognizes Mr. Lionel F. Levy."

MR. LEVY: "Mr. President, I present Edwin H. Land for an award.

"Dr. Land set himself the problem: Was it possible to build a process and construct a hand camera that would, after exposing the picture, deliver shortly thereafter a finished photograph? He did succeed after some years of concentrated research. The ultimate result was a silver halide film rolled after exposure into contact with special paper to which were attached capsules containing concentrated thickened developer. The film and the paper emerge from the camera together with the developer between them. After one minute, the paper is taken off a finished photograph.



EDWIN H. LAND

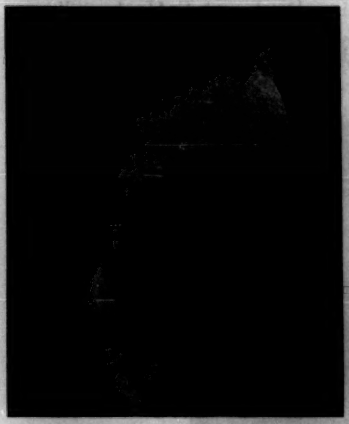
"This Land 'One-step' Camera has proven not alone of interest to general photographers but has many special applications in technology.

"I present Edwin H. Land, of Cambridge, Massachusetts, as a candidate for a Howard N. Potts Medal, 'In consideration of his ingenious development of a practical hand camera and a process to expose and to develop the negative and create a good positive simultaneously, all within approximately a minute.' "

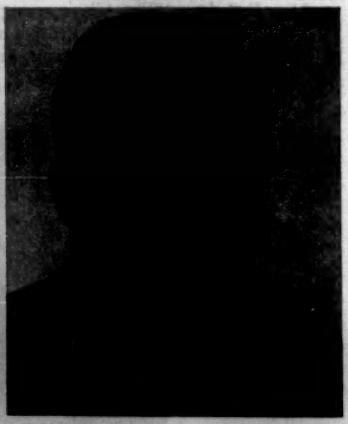
MR. ROLPH: "Dr. Land, by the same authority, I present to you this Howard N. Potts Medal and the Certificate and Report which accompany it."

**PRESENTATION OF THE LOUIS E. LEVY MEDAL**
**(Founded in 1923)**

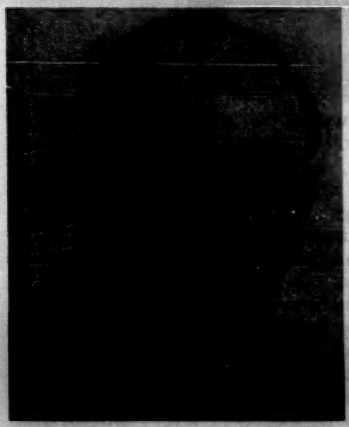
This Medal is awarded to the author of a paper of especial merit, published in the JOURNAL OF THE FRANKLIN INSTITUTE, preference being given to one describing the author's experimental and theoretical researches in a subject of fundamental importance.



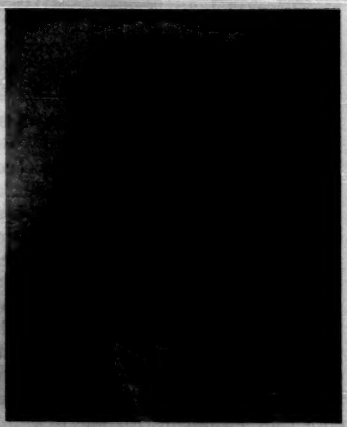
ARTHUR W. BURKS



ROBERT MCNAUGHTON



CARL H. POLLMAR

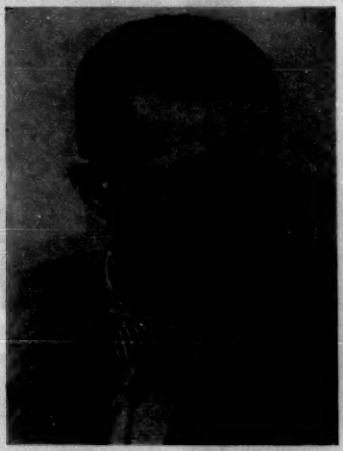


DON W. WARREN

*To Arthur W. Burks, Professor of Philosophy, University of Michigan, Ann Arbor, Michigan; Robert McNaughton, Associate Professor of Philosophy, Stanford University, Palo Alto, California; Carl H. Pollmar, Lecturer in Business Administration, University of Michigan; Don W. Warren and Jesse B. Wright, Research Mathematicians, Engineering Research Institute, University of Michigan.*

MR. ROLPH: "The Chair recognizes Dr. Joseph S. Hepburn."

DR. HEPBURN: "Mr. President, I present Arthur W. Burks, Carl H. Pollmar and Don W. Warren, and, *in absentia*, Robert McNaughton and Jesse B. Wright for an award.



JESSE B. WRIGHT

"Their paper, 'The Folded Tree,' presents the results of a fundamental investigation, carried out at the University of Michigan, into a subject of importance in the design of automata. These automata include electronic computers and other so-called mechanical brains as well as telephone switching systems and devices used in automatic factories.

"A tree is a mathematical model of a system of branches connected together at vertices. A reasonably familiar physical realization is provided by a railway classification yard. Cars from an inbound train can be switched onto either of two tracks at several points. The result is to select the outgoing track by a multiplicity of simple two-way choices.

"This principle, of making a complex choice by repeating a simple choice many times, is embodied in all automatic computing and switching systems, including the human nervous system.

"The main results of the paper concern the *n*-bay tree, not to be confused with the green bay tree. The number of bays corresponds roughly to the number of individual choices which together make up the final choice. In a realization by electromechanical relays, the most obvious arrangement leads to a situation where the further one is removed from the trunk of the tree, the more complex the switching apparatus becomes. It is possible, by means of a technic known as folding, to equalize, in a certain sense, the complexity, by distributing it around the various switching elements. The paper studies the extent to which this equalization is possible and gives a routine process for designing a tree to embody any desired possible degree of equalization.

"I present Arthur W. Burks, Carl H. Pollmar and Don W. Warren, and, *in absentia*, Robert McNaughton and Jesse B. Wright as candidates for the Louis E. Levy Medal, 'In recognition of their outstanding paper, "The Folded Tree," appearing in the July and August, 1955 issues of the JOURNAL OF THE FRANKLIN INSTITUTE.' "

MR. ROLPH: "By the same authority, I present to you Messrs. Burks, Pollmar and Warren, and to Messrs. McNaughton and Wright, *in absentia*, this Louis E. Levy Medal and the Certificates and Reports which accompany it.

"Professor Burks, will you be kind enough to transmit the certificates and reports to Messrs. McNaughton and Wright? This Medal, shared jointly by the gentlemen who have received it, will be placed in the archives of the Engineering Research Institute at the University of Michigan, Ann Arbor, and exhibited there."

**PRESENTATION OF THE FRANK P. BROWN MEDAL**
**(Founded in 1938)**

This Medal is awarded to inventors for discoveries and inventions involving meritorious improvements in the building and allied industries.

*To Robert G. LeTourneau, President, R. G. LeTourneau, Inc., Longview, Texas.*

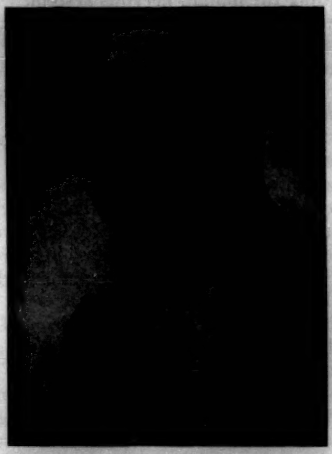
MR. ROLPH: "The Chair recognizes Mr. Joseph Gray Jackson."

MR. JACKSON: "Mr. President, I present Robert G. LeTourneau for an award.

"Mr. LeTourneau is the originator of many of the marvellous new earth moving devices which we see on modern building projects.

"I present Robert G. LeTourneau, of Longview, Texas, as a candidate for the Frank P. Brown Medal, 'For his revolutionary improve-

ments in earth moving equipment, with vast benefit to public works and private building construction.' "



ROBERT G. LETOURNEAU

MR. ROLPH: "Mr. LeTourneau, by the same authority, I present to you this Frank P. Brown Medal and the Certificate and Report which accompany it."

**PRESENTATION OF THE STUART BALLANTINE MEDAL**
**(Founded in 1946)**

This Medal is to be awarded in recognition of outstanding achievement in the fields of Communication and Reconnaissance which employ electromagnetic radiation.

*To Kenneth Bullington, Transmission Systems Engineer, Bell Telephone Laboratories, Inc., Murray Hill, New Jersey.*

MR. ROLPH: "The Chair recognizes Mr. Lewis P. Tabor."

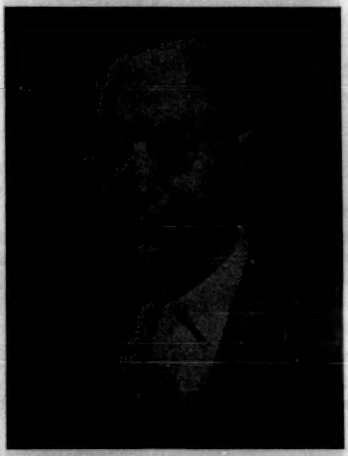
MR. TABOR: "Mr. President, I present Kenneth Bullington for an award.

"The history of technological development occasionally includes a case where a man of rare engineering insight recognizes a potential application for a newly discovered natural phenomenon before a completely satisfying theoretical explanation of this phenomenon has been developed. If this man plans and executes a sound study and meas-

urement program, he can then proceed to design by empirical methods a structure or system which satisfies a technological requirement many years before a design based upon fully developed theory would be possible.

"It is my privilege this evening to present a man whose engineering vision has made possible the development of a new, useful, and practical communications system, using a mode of radio transmission the underlying theory of which is not yet completely understood.

"I present Kenneth Bullington, of Madison, New Jersey, as a candi-



KENNETH BULLINGTON

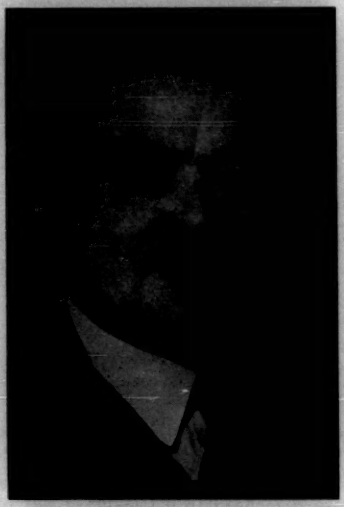
date for the Stuart Ballantine Medal, 'In consideration of his advancement of space communications by means of beyond-the-horizon tropospheric wave propagation which resulted from his vision in recognizing the reliability of this means; his ability in planning and executing a broad experimental program; his engineering interpretation of the results which has led to effective design of communication systems employing this means.'"

MR. ROLPH: "Mr. Bullington, by the same authority, I present to you this Stuart Ballantine Medal and the Certificate and Report which accompany it."

PRESENTATION OF THE FRANKLIN MEDAL
(Founded in 1914)

This Medal is awarded annually to those workers in physical science or technology, without regard to country, whose efforts, in the opinion of the Institute, acting through its Committee on Science and the Arts, have done most to advance a knowledge of physical science or its applications.

*To Frank Whittle, Air Commodore, Longdown, Devonshire, England.*



FRANK WHITTLE

MR. ROLPH: "The Chair recognizes Mr. W. Laurence LePage."

MR. LEPAGE: "Mr. President, I have the honour to present to you, as a candidate for the highest award made by The Franklin Institute, a man of great distinction in the field of aeronautical power plants and the originator and inventor of the gas turbo-jet aircraft engine.

"Air Commodore Sir Frank Whittle is the man who first put reality into the conception that at high altitudes only could the airplane realize to the full its speed potentialities and that only a jet or rocket type of engine could produce efficient power at such altitudes. Such an engine did not then exist.

"I shall not now dwell on the great technical knowledge and ability,

the high skill and the unflagging determination which have characterized this great achievement; these have been fully investigated and chronicled in the report which prompts this presentation. Let me state, however, that from the first, Sir Frank's engines performed with a degree of success and on the very first real test flight, in 1941, the aircraft flew at 370 m.p.h. at 25,000 feet, surpassing by a wide margin the performance of the most successful fighter plane then in war service.

"This remarkable British engineer, who has received Royal recognition of his achievements, has established the basic essential for the broadening of the horizons of aviation beyond all prior conception. Therefore, Sir, upon citation which reads:

" 'In recognition of his vision in realizing the limitations of the conventional propeller type of power plant for high speed aircraft, his conception of the combination of the principles of the gas turbine and the rocket, and his pioneering development of the turbo-jet aircraft engine which has revolutionized high speed flight,'

"I present to you, Frank Whittle, of Longdown, Devonshire, England, as a candidate for The Franklin Medal."

MR. ROLPH: "Sir Frank, as President of The Franklin Institute of the State of Pennsylvania, I present to you this highest award of The Franklin Institute, The Franklin Medal and the Certificate and Report which accompany it, —together with our warmest congratulations."

## ADDRESS BY DR. EDWIN H. LAND

Following the presentation of the Franklin Medal, Mr. Rolph introduced the speaker of the evening, Dr. Edwin H. Land, the Howard N. Potts Medalist. Dr. Land described one-step photography in a talk entitled "From Imbibition to Exhibition."

After Dr. Land had delivered his well-illustrated and informative talk, Mr. Rolph thanked him on behalf of the Institute and dismissed the meeting.

(Dr. Land's address will be published in this JOURNAL for February, 1957)

# THE FRANKLIN INSTITUTE

## MINUTES OF THE STATED MEETING

### November 21, 1956

The Stated Monthly Meeting of The Franklin Institute was held November 21, 1956 in the Lecture Hall. Mr. S. Wyman Rolph, President, called the meeting to order at 8:20 P.M. with approximately 400 members and guests in attendance.

There being no corrections, changes or additions to the minutes of the October Stated Meeting as printed in the November JOURNAL, they were approved as submitted.

The President stated that Air Commodore Sir Frank Whittle, of Rugby, England, Franklin Medalist for 1956, had been nominated by the Board of Managers for Honorary Membership in the Institute and this nomination was now being presented to the members for action. Upon motion duly made and seconded, Sir Frank was unanimously elected to Honorary Membership.

The President then presented Dr. Warren Weaver, Vice President for the Natural and Medical Sciences of the Rockefeller Foundation, who delivered the annual Philip C. Staples Lecture on the subject "Radiation Damage—What Threat Does it Pose to Us and to Our Children" which members found most valuable and thought-provoking.

The meeting adjourned at 9:25 P.M. with a rising vote of thanks to Dr. Weaver.

H. V. BAIL
*Secretary*

## COMMITTEE ON SCIENCE AND THE ARTS

*(Abstract of Proceedings of Stated Meeting held Wednesday, November 14, 1956.)*

HALL OF THE COMMITTEE,
PHILADELPHIA, NOVEMBER 14, 1956.

MR. FRANCIS B. FOLEY in the Chair.

The following reports were presented for final action:

No. 3283: Work of R. J. S. Pigott.

This report recommended the award of an Elliott Cresson Medal to Reginald James Seymour Pigott, of Pittsburgh, Pennsylvania, "In consideration of his engineering accomplishments, including his many valuable inventions, his painstaking research, his notable contributions to the technical press, and his engineering leadership."

No. 3293: Work of Warren W. Carpenter.

This report recommended the award of a John Price Wetherill Medal to Warren W. Carpenter, of Los Angeles, California, "For his important contributions in the field of switching, including the invention of the Automatic Message Accounting System and many related inventions fundamental to the technology of modern telephone switching."

ALAN C. BYERS,
*Secretary pro tempore*

## MEMBERSHIP

### ACTIVE MEMBERS ELECTED BY THE BOARD OF MANAGERS

**November 21, 1956**

**ACTIVE FAMILY**

Edward F. Beale
Frederick C. Binter
Robert Hutton Brown
J. C. Chu
John L. Esterhai
C. G. Grimes
William G. Pierce
G. S. Tompkins

**ACTIVE**

Hyde W. Ballard
William L. Bayer
Howard N. Becker
F. C. Blancha
Arthur F. Cake
J. Presper Eckert, Jr.
Albert Feller
John T. Flanagan, Jr.
Daniel D. Friel
Paul Gibian
Robert P. Haviland
John M. Johnston
Robert N. Jordan
Knut A. Krieger
Edward J. LaVallin, II
Samuel Levy
Ralph V. Little, Jr.
Frederick C. N. Littleton
Maurice E. Long
Russell W. McFall
Thomas Charles McGrath, Jr.
John B. McHugh
Joseph E. McQueen
Walter W. Patchell
Howard S. Pleasants
Philip P. Remer
Merkel W. Ristine
Paul Ruetschi
J. Alison Scott
Morton Scott
J. M. Symes
Mrs. Alfred Wielopolski

**ACTIVE NON-RESIDENT**

Andrus T. Snyder

**NECROLOGY**

William H. Bower '85
William Geftman '55
Frank C. Hoppe '42
Arthur J. Meyer '46
George Washington Pierce '43
John B. Rumbough '08
H. B. Spencer '16

## LIBRARY

The Committee on Library desires to add to the collections any technical works that members may wish to contribute. Contributions will be gratefully acknowledged and placed in the Library. Duplicates received will be transferred to other libraries as gifts of the donor. 345 items have been added the past month.

Photostat service. Photostat prints of any material in the collections can be supplied on request.

The Library and reading room are open from 9 A.M. until 5 P.M. on Mondays, Tuesdays, Thursdays, Fridays and Saturdays; and from 2 P.M. until 10 P.M. on Wednesdays.

### RECENT ADDITIONS

#### AERONAUTICS

BONNEY, E. ARTHUR; ZUCROW, MAURICE J. AND BESSERER, CARL W. Aerodynamics, Propulsion, Structures and Design Practice. 1956.

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#### ASTRONOMY

KOPAL, ZDENĚK, ED. Proceedings of a Symposium on Astronomical Optics and Related Subjects. 1956.

#### ATOMIC ENERGY

UNITED STATES. ATOMIC ENERGY COMMISSION. Conference of the Academy of Sciences of the USSR on the Peaceful Uses of Atomic Energy. 1956.

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## JOURNAL OF THE FRANKLIN INSTITUTE

The following papers will appear in this JOURNAL within the next few months:

FRANK, WALLACE E.: A Study of the Feasibility of Tonal Braille
LAND, EDWIN H.: From Imbibition to Exhibition
MARIN, JOSEPH: Mechanical Properties of Materials for Combined Stresses Based upon True Stress and Strain
HODGE, P. G., JR.: Piecewise Linear Isotropic Plasticity Applied to a Circular Cylindrical Shell with Symmetrical Radial Loading
PIPES, LOUIS A.: Analysis of Electric Circuits Containing Nonlinear Resistance
WEIDLEIN, EDWARD R.: Organizing for Effective Air Pollution Control
HILL, E. L.: Electromagnetic Radiation from Lightning Strokes
SLEPIAN, JOSEPH: The Magneto-Ionic Expander Isotope Separator
PIPES, LOUIS A.: Matrix Problems of Heat Transfer Problems

## NOTES FROM THE FRANKLIN INSTITUTE MUSEUM

A. C. CARLTON, DIRECTOR

### CHAMBERS' MINIATURE ENGINE

In an age when we are torn between the infinitely small and the grotesquely large, the things which fall in between tend to be overlooked. This is especially true when the thing is only an undersized model of a larger original. There is in the Museum more than one model that challenges attention but, in order to draw attention to the Chambers' miniature steam engine, it has been placed in a more conspicuous place in the Lunch-room Lobby and given a more attractive setting.

This particular model is remarkable for more than one feature. To begin with it was made more than a hundred years ago by a boy of sixteen. Then, some of its parts (the steam pipe connecting the boiler with the cylinder, for example) are so intricate in construction that it is something of a mystery how they were made with the tools available at that time. Moreover, this is a genuine steam engine. It was actually steam operated at the Centennial Exposition where it attracted a well merited attention. Today, it is electrically operated because its boiler is made of silver, which is not the most suitable metal for the purpose.

One question which is repeatedly asked is: Did the boy ever do anything worth-while when he grew up? The answer is, yes. Cyrus Chambers, the model's maker, had some 75 patents granted for his inventions before he died in 1911, in his 75th year. He began inventing at an early age. He was only 22 when he patented the basic design for paper-folding machines for books. The work of folding the "signatures" from which books are produced had formerly been done by girls. The modern paper-folding machinery embodies the combination of serrated blades, knurled rollers, and tapes to be found in the machine Chambers marketed in 1856.

Manufacture was carried out in company with his elder brother Edwin, who had been trained as a dentist, but the outbreak of the Civil War caused the brothers to adjust the plant to the production of sword scabbards. During the period of hostilities, Cyrus was occupied with experiments which culminated in his second basic invention, the brick-making machine. The use of the augur for extrusion was not new, but Chambers combined this with an automatic cutter regulated to the speed of the clay bar. The result was to produce bricks of uniform size no matter at what speed the clay streamed through the machine. The first of these machines went into operation at Fish House, N. J. in 1868.

Most of his other patents that proved profitable related to the paper-folding and brick-making machines which he improved. Very shortly after the introduction of the latter machine, Chambers had improved it to such an extent that he was able to produce 25,000 bricks an hour. Affluence came after the disastrous fire in Chicago. The decision of that city's authorities not to allow the use of wood in reconstruction gave a tremendous impulse to brick manufacture, and it is hardly an exaggeration to say that the city was rebuilt with Chambers' machine-made bricks.

Chambers never stopped working and inventing, although for the last fifteen years of his life he was almost blind. As early as 1907 he was engaged in experimenting with an engine that would enable an airplane to make a vertical take-off. When the first airplane landed in Philadelphia he was on hand to "see" it through the eyes of his younger assistants, and he declared emphatically that was the wrong way for an airplane to land. He lamented his age and blindness denied him from correcting the fault.

The Chambers Brothers Company is still flourishing in Philadelphia under the ownership of the founder's direct descendants.

However, in spite of his great accomplishments the Museum visitor will still approach with mingled admiration and wonder, the tiny little walking beam engine he built (tradition says, from his mother's silver teaspoons) in 1849. We believe it is the smallest operating steam engine in existence. It consists of more than 150 separate pieces, and weighs slightly more than one-half ounce. The maximum speed is 3000 revolutions a minute, but it is now run at reduced speed to make the movement discernible. The fuel consumption, so far as we know, has never been computed.

NOTES FROM THE FRANKLIN INSTITUTE LABORATORIES
FOR RESEARCH AND DEVELOPMENT
NICOL H. SMITH, DIRECTOR

## RHEOLOGY GROUP

BY

W. PHILIPPOFF

The Rheology Group was set up in the Colloids Section of the Chemistry and Physics Division of the Laboratories in July 1955. Rheology, as is well known, is the science of flow, or more generally speaking, the science of the mechanical behavior of materials, especially those that are neither Newtonian liquids nor elastic solids. The scope of work extends from the mathematical foundations of deformational mechanics down to purely practical applications in bending, tension or shear of technological specimens. The materials involved have properties that depend both on *time* and on the magnitude of applied *stress*. Furthermore, as any other physical properties they are also dependent on *temperature*.

As has been realized, and extensively confirmed in these Laboratories, a large range of variables is essential for the description of the properties as determined by the three variables mentioned. We have developed a collection of instruments that allow us to measure the properties as function of the three variables mentioned, to practical limits as follows: The temperature range is from $-23°$ C. to $+300°$ C.; the rates of shear in steady flow range from $10^{-7}$ sec$^{-1}$ to $10^{6}$ sec$^{-1}$; the frequency at each temperature from $5 \times 10^{-6}$ to 10 cps. All this is far in excess of anything available elsewhere.

The emphasis has been to correlate all the instruments so that their respective ranges can be used for measurements in extended ranges without much overlap. For investigation of steady flow, we have rotational instruments and capillary instruments to cover a range of thirteen decades ($10^{13}$) in the rate of shear. The vibration tester that was developed under the sponsorship of the National Asphalt Research Center allows the investigation of a variety of materials with suitable attachments in the whole stated range of frequencies and temperatures: polymer solutions, asphalts, solid plastics, greases, metals and masonry. The use of the "reduced variables" introduced by J. D. Ferry allows one to correlate the results at different temperatures and frequencies to obtain so-called "reduced curves" that describe the change in properties, with time and temperature, in a range of up to 40 decades ($10^{40}$)

in reduced frequency or time. Recently, for the Army Chemical Corps, a flow birefringence instrument has been designed and built which incorporates the major advances in the field of optical equipment; this has been made suitable for nearly as wide a range of rates of shear as the other instruments: namely, from $3 \times 10^{-4}$ to $3 \times 10^{+4}$ $sec^{-1}$, that is a range of 1 to 100,000,000. Furthermore, through the same sponsor a Weissenberg Rheogonimeter is available. This instrument, developed in England, is probably the only one of its kind in the United States.

Flow birefringence apparatus.

Due to the theoretical and experimental work in the field, we have been able to correlate the results of the flow birefringence instrument and the Weissenberg Rheogonimeter, with new insight into the rheology of polymer solutions.

The Group had been handling rheology projects on a variety of substances, such as chewing gum, lime mortars, phonograph records, polyethylene and other plastics, lubricants, etc. The possibility of having all the instruments designed for rheological investigations in one laboratory allows one to investigate any kind of material in a most complete fashion, which permits an adequate description of its properties for any type of practical application.

The most recent publication from the Group is a paper entitled "Flow Birefringence and Stress."[1] The abstract of this paper informs us that "simultaneous measurements of flow birefringence, shear and normal stresses on a 15 per cent solution of polyisobutylene in decalin were performed. They proved that the extinction angle measured in birefringence is identical to the orientation of the principal tensile stress calculated from the normal stress measurements and that the birefringence was proportional to the difference in principal stresses in flow. A detailed discussion of the significance of this result is given with a possibility of a far-reaching generalization of the mechanical behavior of high polymer solutions."

[1] W. PHILIPPOFF, "Flow Birefringence and Stress," *J. Appl. Phys.*, Vol. 27, p. 984 (1956).

## PUBLICATIONS RECEIVED

The Editors wish to call attention to these new books which have been received in the JOURNAL office for review. Lack of space prevents publication of full reviews.

CONTRACTS, SPECIFICATIONS AND ENGINEERING RELATIONS, by Daniel W. Mean and Joseph Reid Akerman. Third edition, 427 pages, 6 × 9 in. New York, McGraw-Hill Book Co., Inc., 1956. Price, $7.00.

AN INTRODUCTORY COURSE IN COLLEGE PHYSICS, by Newton Henry Black and Elbert Payson Little. Fourth edition, 786 pages, illustrations, 5½ × 8½ in. New York, The Macmillan Company, 1956. Price, $6.75.

U. S. ARMY IN WORLD WAR II. THE TECHNICAL SERVICES. THE SIGNAL CORPS: THE EMERGENCY, by Dulany Terrett. 354 pages, illustrations, 7 × 9¾ in. Washington, Government Printing Office, 1956. Price, $3.50.

MASS SPECTROMETER RESEARCHES, by G. P. Barnard. 62 pages, plates, diagrams, 6 × 9½ in. London, Her Majesty's Stationery Office, 1956. Price: 3s 6d; 63¢ U. S. A.; by post, 3s 9½d.

WIND AND TEMPERATURE TO 50 KM. OVER ENGLAND, by R. J. Murgatroyd. Geophysical Memoirs No. 95, 30 pages, diagrams, 8½ × 11 in. London, Her Majesty's Stationery Office, 1955. Price, 5s.

INFINITE SEQUENCES AND SERIES, by Konrad Knopp, translated by F. Bagemihl. 186 pages, 5½ × 8 in. New York, Dover Publications, Inc., 1956. Price: $3.50 (cloth); $1.75 (paper).


## TO MEMBERS AND THOSE WHO KNOW THE FRANKLIN INSTITUTE

**All of us associated with The Franklin Institute are gratified by the support given by its benefactors in the past. Without their generosity our privately endowed Institute would have been unable to serve industry, the professions, and the public as it has and should.**

**There is still a continuing and pressing need of contributions and bequests —both for general and specific endowment, and of income to be judiciously used. Your response will be most earnestly appreciated.**

**Checks should be made payable to The Franklin Institute, and sent to The Franklin Institute, Benjamin Franklin Parkway at 20th Street, Philadelphia 3, Pennsylvania.**

**Where property is transferred, title should be in the name of The Franklin Institute of the State of Pennsylvania for the Promotion of the Mechanic Arts.**

**We shall be glad to supply any additional information regarding gifts and memorials. Please write to the above address, attention of the Endowment Department.**

NOTES FROM THE BIOCHEMICAL RESEARCH FOUNDATION
ELLICE McDONALD, M.D., FOUNDER WILLIAM G. BATT, D.Sc., DIRECTOR

# PROPERTIES OF KREBS 2 ASCITES CARCINOMA CELLS: WEIGHT, SIZE, SPECIFIC GRAVITY, AND PROTEIN CONTENT

BY

W. D. YUSHOK, LOIS J. MALLALIEU AND WILLIAM G. BATT

Extensive investigations of metabolic activities and other properties of Krebs 2 ascites carcinoma cells have been in progress in this laboratory since 1952. This ascites tumor, which consists of a nearly homogeneous population of cancer cells in the peritoneal cavity of the mouse, has been found to lend itself to precise quantitative determination of chemical and physical properties to an extent that is not attainable with solid tissue. It permits the evaluation of activities of a predetermined number of cancer cells.

Although the number of cells is the preferable reference for expressing metabolic rates of both cell suspensions and solid tissue, the dry weight of tissue slices is conventionally the standard of reference. The dry weight basis is generally used, not because it is the best estimate of the active metabolizing material present, but because of the technical difficulties involved in estimating the living cell mass by other methods.

In the present study, the dry weight of the ascites cells was determined in order to calculate metabolic rates on this basis for comparison with the rates of solid tissues reported in the literature. The wet weight and protein content of Krebs cells were also estimated, since the metabolic rates of tissue slices and homogenates are occasionally reported on these bases.

In addition, it was considered desirable to estimate the volume, diameter, and specific gravity, since a search of the literature did not reveal any data on these characteristics of the Krebs cell. The packed cell volume, which can be easily determined by centrifugation of cell suspensions in Bauer-Schenk tubes, is used routinely as a reference in this laboratory.

## MATERIAL AND METHODS

The Krebs 2 ascites carcinoma was propagated in female white Swiss mice by intraperitoneal injection of 0.05 ml. of the ascitic fluid from mice bearing 7-day-old ascites tumor. For the cell determinations, ascitic fluid was withdrawn from 2 to 4 animals 6 to 8 days following

inoculation. From 3 to 5 ml. of ascitic fluid was added to a graduated centrifuge tube, followed by cold Krebs-Henseleit bicarbonate buffer to bring the total volume to 15 ml. The Krebs cells were prepared by repeated centrifugations at low velocity for short periods, each followed by a resuspension in buffer under conditions which were described in a preceding publication (1).

Cell counts, wet weights, and dry weights were determined by previously reported procedures (1). The specific gravity of the cells was determined on suspensions in which the volume of cells was approximately 20 to 25 per cent of the total volume. Into each tared Bauer-Schenk tube of 3 ml. capacity, exactly 2 ml. of cell suspension were pipetted. After the cells were spun down in a refrigerated centrifuge at 2500 *g* for a 40-minute period, the packed cell volume was read. The centrifugal force was calculated for the midpoint of the tube. Most of the supernatant fluid was removed by blotting with a pipe cleaner, and the tubes were weighed in order to determine the cell wet weight.

The specific gravity of the cells was calculated from the wet weight and total volume, which were both determined on the same cell populations. The mean values of the wet weight and specific gravity were used in approximating the cell volume. The diameter of the average cell of the population was calculated from the average volume assuming a spherical cell shape.

The protein content was analyzed by the method of Lowry *et al* (2). Crystalline bovine plasma albumin (Armour) was used as the standard.

## RESULTS AND DISCUSSION

The values of some properties of Krebs 2 ascites cells are presented in Table I. One million Krebs cells were found to contain 2.77 milli-

TABLE I.—*Some Properties of Krebs 2 Ascites Cells.*

| Property | Unit of Measurement | Mean Value | Standard Error of the Mean | No. of Determinations |
|---|---|---|---|---|
| Wet Weight | Milligrams/$10^6$ cells | 2.77 | 0.01 | 23 |
| Dry Weight | Milligrams/$10^6$ cells | 0.462 | 0.003 | 13 |
| Dry Matter | Per cent of wet weight | 16.7 | 0.01 | 10 |
| Specific Gravity | — | 1.037 | 0.001 | 14 |
| Protein Content | Milligrams/$10^6$ cells | 0.300 | 0.002 | 10 |
| Cell Volume | Microliters/$10^6$ cells | 2.67 | — | calcd. |
| Cell Diameter | Microns | 17.2 | — | calcd. |

grams wet weight, 0.462 milligrams dry weight, and 0.300 milligrams protein.

The volume of an average Krebs cell was found to be $2.67 \times 10^{-6}$ microliters or 2670 cubic microns. The Krebs cell, therefore, is approximately 54 times larger in volume than the red blood cell, which was reported to be 49 cubic microns (3). The Ehrlich ascites carcinoma cell was reported to have a volume of 2485 cubic microns (4). The cell

volumes of both ascites tumors are of approximately the same order of magnitude, the mean for the Krebs cell being only 7 per cent greater than that of the Ehrlich cell.

Conversion factors to facilitate calculation from one reference state to another are given in Table II.

TABLE II.—*Equivalent Values of Properties of Krebs 2 Ascites Tumor.*

| | Dry Weight | Cell Volume | Protein Content |
|---|---|---|---|
| | one milligram equivalent to | ten microliters equivalent to | one milligram equivalent to |
| Dry Weight, milligrams | — | 1.73 | 1.54 |
| Wet Weight, milligrams | 6.00 | 10.37 | 9.23 |
| Cell Volume, microliters | 5.78 | — | 8.90 |
| Cell Number, millions | 2.17 | 3.75 | 3.30 |
| Protein, milligrams | 0.649 | 1.12 | — |

Protein was found to constitute 64.9 per cent of the dry matter of the Krebs cells. This value falls within the range of protein content of various neoplastic and normal tissues grown in tissue culture by Oyama and Eagle (5). On a cell basis on the other hand, the total protein content of the Krebs tumor was significantly lower than the ones reported (5) for cells grown in tissue culture.

SUMMARY

Some physical and chemical properties of the Krebs 2 ascites carcinoma cell were determined: namely dry weight, wet weight, volume, diameter, specific gravity, and protein content.

Factors were calculated for converting metabolic rates of the Krebs 2 ascites tumor from one reference state to another.

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## BOOK REVIEWS

POLYESTERS AND THEIR APPLICATIONS, by J. Bjorksten, H. Tovey, B. Harker, and J. Henning. 618 pages, 6 × 9 in. New York, Reinhold Publishing Corp., 1956. Price, $10.00.

The polyesters, like so many of the other resinous materials, have developed their own chemistry, engineering, modifications, and end item applications. Their wide acceptance and use in a broad variety of commercial applications (aircraft, boats, automobiles, electrical and industrial equipment, home furnishings, office equipment, sporting goods, etc.) have brought along the expected flood of publications. The authors, in this book, have tried to provide a reasonably up-to-date (June 1954) survey of literature and patent references covering the various phases in polyester applications.

The book itself is divided into five major parts covering the following subjects: theory of formation and chemical structures of the polyesters, production and uses of unsaturated polyesters, production and uses of saturated (fiber forming and diisocyanate modified) polyesters, methods for testing raw materials, finished products, catalysts, and fillers, and manufacture and fabrication health hazards. In addition almost one-half of the book is devoted to a very extensive and carefully annotated bibliography of literature and patent references on which the bulk of the text is based. A short supplement included at the end of the book provides a very brief survey of developments with polyesters from June 1954 to the Spring of 1956 when the book was printed.

The authors apparently have achieved their purpose of presenting a comprehensive survey of the entire field of polyester applications, but, in the opinion of the reviewer, it is unfortunate that they did not select only one or two of the subjects described above for more thorough presentation. For example, a book just on the advances in the chemistry, engineering, and formulation of the saturated and unsaturated polyesters would indeed be welcome to both research and development workers in the field. Likewise a volume is needed that surveys the effects of the various engineering and manufacturing variables on the molding, preforming, casting and laminating of the polyesters. While all of these subjects are discussed, the coverage is disappointingly cursory. However, this present book does serve its purpose, and is worthwhile just from the standpoint of the excellent bibliography alone. It is certainly the most up-to-date reference work in the field, and will undoubtedly be of great value to those workers concerned with polyester applications.

D. H. RUSSELL

LINEAR TRANSIENT ANALYSIS, Volume II, by Ernst Weber. 452 pages, diagrams, 6 × 9 in. New York, John Wiley & Sons, Inc., 1956. Price, $10.50.

The vast strides made in the electrical and electronics fields in the past few decades have resulted in increasingly complicated circuitry capable of performing functions which were impossible just a short time ago. As a result, the engineer today is confronted with highly complex problems of circuit design and analysis requiring an advanced knowledge of network theory. The present text offers help with these problems by discussing the application of Fourier and Laplace transforms to the transient analysis of linear two-terminal-pair networks and transmission lines.

Professor Weber has had the benefit of many years of teaching and working experience in this field. The value of this experience is evidenced in the text by a clear, concise approach to the problem. Volume II of this series follows logically after Volume I and presents an unusually comprehensive treatment of the two-terminal-pair network. The text is planned for the graduate student. Consequently, a knowledge of complex variable theory and a familiarity with simple lumped circuits is presupposed. However, the author has added a number of appendices which cover many of the essentials of such prerequisites, and help make the work self-sufficient.

The book is divided into two parts. The first section, Chapters 1 through 5, covers the subjects of wave filters, passive four-pole lines, idealization of network characteristics, and active fourpoles such as tubes and transistors in the linear region. The very first chapter contains a brief review of the Fourier and Laplace transform methods. The second part of the book beginning with Chapter 6 is devoted to discussions of transmission systems, beginning first with a qualitative analysis of the physical phenomena involved in systems with distributed parameters. Chapter 7 is devoted to the ideal cable and Chapter 8 concludes the text with a presentation of approximations and the rigorous solution for the general transmission line.

Enough examples are included in the book to carry the reader through the more difficult concepts and clinch the theoretical developments. Problems are given at the end of each chapter, and it is presumed that the answers are available from the publisher. They would be a great aid to the student studying the text independently. The subject matter treated here is fairly complex, but Professor Weber is careful to provide very complete developments of the theory and a large bibliography to refer the reader to numerous additional papers as the need arises. The text is carefully and well written. While intended primarily for students, practicing engineers, because of the great importance of this subject to their work, will be sure to regard the book as a sound investment.

D. L. BIRX

PHYSICS AND CHEMISTRY OF THE EARTH, edited by L. H. Ahrens, K. Rankama and S. K. Runcorn. 317 pages, diagrams, 6 × 9 in. New York, McGraw-Hill Book Co., Inc., 1956. Price, $8.00.

One of the most curious aspects of our earth is that we are so closely bound to the surface. We cannot go above the surface without continuously expending energy of considerable magnitude. We cannot dig deep beneath the surface without again expending energy. We live on the surface. We can explore most of the surface and those places formerly inaccessible to us have succumbed under the inexorable onslaught of explorers. We are done with the surface and now the mystery lies beneath the surface. What materials lie there? How hot is it? How old are the rocks? And perhaps most intriguing of all these questions is: How did this earth come into being?

To answer some of these questions, L. H. Ahrens of Oxford University, Kaleroo Rankama of the University of Helsinki, and S. K. Runcorn of King's College, the editors of *Physics and Chemistry of the Earth*, have invited many internationally known and ranking students of the earth sciences to bring various facets of the earth sciences into sharp focus.

In the eight sections of the book we find Sir Harold Spencer Jones, the ex-Astronomer Royal, leading off discussing the origin of the solar system. To this there is no definitive answer, but everything known about this phenomenon is detailed in the rather short section. Sir Harold clearly shows how the existing theories are wanting and as of this moment the question of the origin remains a mystery.

Temperatures within the earth are analyzed and the author sums up his review of this work by saying " . . . no inconsistencies arise at present from the assumption that the average gradient in the mantle is about 0.6 degrees per kilometer, the temperature at the core boundary being around 3000 degrees per kilometer."

One of the editors, Dr. Ahrens, discusses radioactive methods for determining geological age. In this section he analyzes and evaluates the various methods used in this field.

Seismology and the broad structure of the Earth's interior is Dr. K. E. Bullen's contribution. In this section the various models of the Earth's structure, as defined by the passage of earthquake waves, are described.

Raymond Hide's contribution is on the hydrodynamics of the earth's core. Here are two major problems. The first is the source of energy which powers the fluid motion of the core, and the second is the dynamics of the fluid motion, that is, the behavior of the flow in time and space.

The remaining three sections deal with the hydrothermal conditions of the earth, the geochemistry of the halogens and geochemistry in the Soviet Union.

*Physics and Chemistry of the Earth* represents a survey of progress for some facets of earth study.

I. M. LEVITT

PRINCIPLES OF COLOR TELEVISION, edited by Knox McIlwain and C. E. Dean. 595 pages, diagrams, 6 × 9 in. New York, John Wiley & Sons, Inc., 1956. Price, $13.00.

Containing nearly 600 pages of engineering principles and techniques which pertain to the most recent color television practices, this book is a credit to its authors and editors. Twelve members of the Hazeltine Laboratories have combined their efforts to produce this engineering reference on the present state of color circuit developments. Most of these engineers have previously made notable contributions to the literature in the television field and are through their experience well qualified to participate in the preparation of a book on the subject. In the September '56 issue of the *Proceedings of the Institute of Radio Engineers* Donald Richman makes further recommendations for the technological improvement of the NTSC specifications.

The most satisfactory aspect of this book to impress the reviewer is that it does not rehash the fundamental principles of electronic tube circuits, a common failing of many engineering texts recently published. On the contrary, these authors have used the available pages well by sticking strictly to modern color television. Nor has space been wasted reviewing black and white circuits.

The book strikes a discriminating course between the wholely descriptive and the academically mathematical. This should please the practicing engineer who is called upon to solve difficult circuit problems but who must not spend time with mathematical exercises for their own sake.

A considerable portion of the descriptive material deals with those interesting and important physical aspects of color which the television engineer should find helpful in thinking about system problems. The physics of light and photometry, color perception, and colorimetry are treated in a somewhat more detailed fashion than has been the tradition in standard works on television engineering.

Within this single volume the authors have concentrated specific circuit information on the equipment for producing the transmitted signal, receivers, decoders for one and three-gun displays, synchronization, and measuring devices. Extensive bibliographies of fifty or more references supplement each chapter.

For those practicing in the field of television engineering this book will in all probability become a valued reference. It is less likely to be useful as a teaching text because it assumes a considerable base of engineering knowledge on the part of the user. However, its position as a reference is assured for some time to come, since it deals with a number of developments which have not as yet even reached the consumer.

C. W. HARGENS

CATALYSIS, VOL. 4, HYDROCARBON SYNTHESIS, HYDROGENATION AND CYCLIZATION, edited by Paul H. Emmett. 570 pages, diagrams, 6 × 9 in. New York, Reinhold Publishing Corp., 1956. Price, $12.50.

The need for detailed information on the mechanism of hydrocarbon formation becomes more urgent with our changing markets and economics, in addition to the desire for more knowledge on this complex phenomenon of catalysis. This volume of the Catalysis series contains a very comprehensive treatment of the Fischer-Tropsch synthesis which extends the earlier publication on this subject by H. H. Storch, N. Golumbic and R. B. Anderson in 1951. The large volume of data presented on the Fischer-Tropsch reaction has led to considerable speculation on the mechanism; however, Dr. Anderson has treated it conservatively throughout his contribution of the first three chapters.

Chapter 4 on Crystalline Phases and their Relations to Fischer-Tropsch Catalysts by L. J. E. Hofer is a concise survey of studies of iron, cobalt and nickel systems principally with some reference to the metals of the platinum group. The difficulties in attempts to explain certain specific catalytic activities on electron structure are briefly presented and noted that such an approach is impossible with such complex alloy systems used in the Fischer-Tropsch catalysts. The effect on catalytic activity through formation of various carbides, nitrides, oxides, and borides is discussed.

The isosynthesis is reviewed in Chapter 5 by E. M. Cohn. This process results in products which are predominately saturated, branched chain, aliphatic hydrocarbons having four to eight carbon atoms. The catalysts are single and multicomponent types derived by precipitation as oxides of such metals as thorium, aluminum, tungsten, uranium and zinc. Born of necessity during World War

II, this process as yet, has not reached commercial importance. It offers another system in which to study mechanism of formation of hydrocarbons.

Methanation in Chapter 6 has been effectively concentrated by Murray Greyson. Interest in this reaction has been quite diverse but probably the quest for knowledge has been more to be able to suppress the reaction in the case of methanol synthesis or to revert the product in the Fischer-Tropsch synthesis. Iron, cobalt and nickel catalysts appear to be the most suitable for methanation. The present volume of Catalysis would be incomplete without consideration of this reaction and the materials which promote it.

Catalysis in the Liquid-Phase Hydrogenation of Coal and Tar (Chapter 7) has been analyzed by S. W. Weller. The complexity of the raw materials for this reaction has undoubtedly been a deterrent to many attempts for a detailed study of its mechanism.

Metal oxides of the 5th and 6th sub-group of the periodic table are generally employed in catalytic cyclization and aromatization which is described in the final chapter by H. Steiner. In spite of the complexity of the products formed, more detailed knowledge has been accumulated on possible mechanisms for these reactions. Much of this activity has been prompted by industrial success of such processes.

The editor has commendably avoided any but the necessary repetition in the separate chapters in the present volume and in other volumes in the series. Thus, Catalysis—Volume 4 serves a needed position for reference for the scientific worker as well as the advanced student in this field.

R. S. DALTER

COMPUTERS; THEIR OPERATION AND APPLICATIONS, by E. C. Berkeley and Lawrence Wainwright. 366 pages, diagrams, 6 × 9 in. New York, Reinhold Publishing Corp., 1956. Price, $8.00.

In the preface the authors say this book is in many ways a sequal to its predecessor, "Giant Brains or Machines that Think." They also point out it discusses certain topics in the field of machinery that handles information and omits discussion of many other topics. This is very true and suggests a brief review of what is actually in the book and what is not.

The authors assume no prior knowledge of computers on the part of the reader. They define "computer" and discuss various types and trends. Both analog and digital are treated with examples. A logical presentation is given of the components of such machines as well as a list of automatic computers. In examples of analog computers, mechanical and electronic differential analyzers and harmonic analyzers are treated, but digital differential analyzers are not. Considerable attention is given to miniature computers, notably Simon, in which Mr. Berkeley has a personal interest. A surprisingly complete discussion of Sperry Rand's Univac is included as well as consideration of the International Business Machines 700 series of computers. The ERA 1103, or Univac-Scientific, is treated and these constitute the large machines discussed. Although the analog computers are well handled as are the large electronic and miniature Simon, the wide gap between the miniature and large digital computers is not filled in at all. An entire chapter is devoted to applications of automatic computing machines. Included is an unusual section on military applications of analog computers written by Dr. Wainwright. The rest of the book is the work of Mr. Berkeley. A set of references, roster of organizations making automatic computing machines, roster of automatic computing services, and glossary of terms and expressions conclude the text. Most of this concluding material comes from the magazine "Computers and Automation" edited by Mr. Berkeley.

It is not surprising that in a field growing as rapidly as this one there is a shortage of good reference material. This book is recommended to help alleviate this situation. It is excellent for the beginner and even those working in the field will find new material here and will use the book for occasional reference. The authors are to be commended for writing a very usable book in a large and fast-growing field—a field that is changing industry and catching the imagination of the populace.

DONALD B. HOUGHTON

SYNTHETIC ION-EXCHANGERS, by G. H. Osborn. 194 pages diagrams, 5½ × 8½ in. New York, The Macmillan Co., 1956. Price, $6.00.

The life of the synthetic ion-exchange resins covers only about the last twenty years. Yet

in this relatively short period of time these products have graduated from laboratory curiosities to potentially some of the most valuable tools available to industry and science. Uses for the ion-exchangers embrace many fields, but the author covers the most important ones, namely: analytical chemistry (frontal, elution, and displacement chromatography, ionophoresis, amphoteric separations, redox reactions, etc.), ion-exclusion (separation of ionic from non-ionic materials by selective reactions), solubilization of insoluble inorganic salts, ion exchange membranes for selective ion permeability, and many specialized therapeutic applications in which advantage is taken of the specificity of the resins (treatment of acidosis and hypopotassemia as examples).

The author, a true expert on ion-exchangers, realized that the knowledge and application of these materials is mushrooming, and that the scientist who must use them cannot possibly keep up with the flood of literature on new types and uses of, and theories on, ion-exchangers. He has therefore prepared this little book in which he critically reviews all of the latest advances in both the science and technology, and then provides a comprehensive bibliography for the worker who needs more detailed information on specific subjects. This very extensive bibliography is divided into two parts. The first section, arranged according to subject, covers applications and the second part, arranged according to author, lists publications on theoretical aspects.

This book represents a rather refreshing departure from the usual attempt to comprehensively cover a branch of science in a single text. It is at once both a resume of the author's expert opinion of the field as a whole and a ready source of reference of the most current information on the subject. Scientists concerned with either the development or the application of ion-exchangers should most certainly add this valuable work to their book shelf.

D. H. RUSSELL

PULSE AND DIGITAL CIRCUITS, by Jacob Millman and Herbert Taub. 687 pages, diagrams, 6 × 9 in. New York, McGraw-Hill Book Co., Inc., 1956. Price, $12.50.

Historically we may place Millman's and Taub's new book among those fostered by an era of computer, television, and radar development. The important thread of pulse circuit technology from all three of these distinct fields has been incorporated in this work. In general one can say too that the scientific personnel working in one of these fields are rather singly devoted to their specialties and seldom double for instance as television and computer engineer. Specialized company interests as well as the enormous complexity of these highly developed fields are factors responsible in forcing the engineer to make a choice of only one.

In view of this tendency it is evident that the subjects covered in the book cut significantly across a very large segment of contemporary electrical engineering activity. When used as a text for the instruction of students in any of these electronics and communications subjects, this book will contribute to their understanding of pulse circuits regardless of later specialization.

The method of presenting subjects has been to give circuits for doing various jobs and accompany them with a word description of their operation. In some cases a mathematical analysis of the effect of important parameters is included. Most of the book deals with vacuum tube circuits, but a final chapter takes up transistors and their use in accomplishing some of the pulse forming and counting operations.

As one reads, there exists an impression of the authors' brevity in passing from one type of circuit to another. In consequence of such abridgement it would be essential to accompany the teaching of these subjects with some experimental experience. By thus illustrating in the laboratory the devices that are being discussed, practical visualization of useful circuits would be more surely achieved. Following a thorough grounding in basic electron tube and circuit theory through prerequisite studies, this volume should provide excellent preparation for professional circuit applications practice.

C. W. HARGENS

NUMERICAL ANALYSIS, VOL. VI, edited by John H. Curtiss. 303 pages, graphs, $9\frac{1}{4} \times 6\frac{1}{4}$ in. New York, McGraw-Hill Book Co., Inc., 1956. Price, $9.75.

Included in this volume are all but two of the papers presented at the Sixth Symposium in Applied Mathematics of the American

Mathematical Society, held at Santa Monica City College, Santa Monica, Calif., August 26 to 28, 1953. The topics represented in the nineteen articles are diversified but are not entirely unrelated. In fact, four of the papers are concerned with methods applicable to finding solutions to systems of linear algebraic equations, and to certain ordinary and partial differential equations. In this group J. W. Fischback's paper, "Some Applications of Gradient Methods," serves almost as an introduction to two other papers, *viz.*, "The Conjugate-Gradient Method for Solving Linear Systems," by M. R. Hestenes and "The Method of Steepest Descent," by P. C. Rosenbloom. Another article in this group, by D. Young, is entitled "On the Solution of Linear Systems by Iteration."

Certain problems in Number Theory and their solutions via digital computers are discussed in three other papers. One of these, by R. H. Bruck, contains a rather provocative challenge to the computing industry to obtain solutions to a certain class of problems which has received considerable attention in the past by C. F. Gauss and L. E. Dickson.

The remaining papers deal with problems arising from Decision Theory, Boundary value problems and Stability considerations in Partial Differential Equations, Conformal Mapping by Numerical Methods, Integral Equations, polynomial and rational function approximations, Asymptotic Transformation of Certain Distributions into the Normal Distribution, Function Spaces and Approximation, Shock Configuration in Mach Reflection and problems whose variables are permutations.

This book is by no means a text. Most of the papers appear in a condensed form and will not be easily read by the nonspecialist. Fortunately, in practically all cases, an excellent bibliography appears with each presentation.

Some of the most outstanding persons in contemporary mathematics have contributed to this volume—E. Lehmer, T. S. Motzkin, O. Taussky, C. Hastings, together with those already mentioned are but a few. This collection of papers, therefore, reflects in one volume some of the most advanced thinking in Numerical Analysis today. It is interesting to observe the tremendous influence that the advent of high speed digital computers has had in directing current progress in Numerical Analysis. LAURENCE C. MCGINN

THE NUMBER-SYSTEM, by H. A. Thurston. 134 pages, $5\frac{1}{4} \times 8\frac{1}{4}$ in. New York and London, Interscience Publishers, 1956. Price, $2.50.

This little monograph of somewhat over 100 pages is concerned with the development of the real number system. The development begins with the Peano axiom and proceeds using Cauchy sequences. It uses the algebraic notions of hemigroups, groups and fields.

The subject matter is essentially that of Landau's classic "Grundlagen der Analysis." However, the treatment is different because of the algebraic concepts introduced by the author of this little book.

Like Landau's book, this one is suitable as part of a rigorous course in analysis. It will also have the further advantage of introducing the student to some modern algebraic concepts. However, only about one half of this book is devoted to the rigorous development. The book is divided into two parts. Part I is called Explanatory Treatment, while Part II is called Systematic Treatment. The first half is, therefore, an expository discussion of the material treated rigorously in the second half. This first part should appeal to the general reader who might be interested in finding out what an axiomatic development of the number system is like. The first part should also be of help to the mathematical student struggling with the lemmas and theorems of Part II. H. L. PLATZER

# BOOK NOTES

HANDBOOK OF SCIENTIFIC AND TECHNICAL AWARDS IN THE UNITED STATES AND CANADA, 1900–1952, edited by Margaret A. Firth. New York, Special Libraries Assn., 1956. Price, $10.00.

A vast amount of research has gone into the preparation of this useful volume listing the most important scientific awards made by technical societies in the United States and Canada from 1900 to 1952. Further, the material has been arranged so that the information is readily available to the reader.

The U.S. and Canadian lists are separated and each list is further subdivided into an alphabetical list of the awarding organizations. Under each of these associations are listed the names of the awards they bestow (with a short description of each award); the recipients of these awards are listed under each, in chronological order. Publication references to the accompanying citations are included for the awards given from 1929 on. Also listed are biographical references for the recipients, and a reference to the published paper (if any) presented on the occasion of the acceptance of the award.

By far the easiest way to use the compilation is to refer to the complete "Index of Recipients and Award Titles" which occupies 64 pages of the book. An additional "Subject Index" of five pages will be of use to those looking for awards in specific fields.

Special Libraries Association is to be commended for sponsoring the publication of this useful listing. It will prove invaluable to award committees both in considering establishment of new awards and in judging the cases for already established ones. It should also prove a boon to all science libraries, whose librarians are constantly asked to furnish such information.

The Franklin Institute's list of medals and certificates of merit occupies 22 pages of the book and makes this compilation of especial value to JOURNAL readers and Institute members.

THE ART OF ARCHITECTURE, by Sir Albert Richardson and Hector O. Corfiato. Third edition, 663 pages, plates, 6½ × 9½ in. New York, Philosophical Library, 1956. Price, $25.00.

This is the third revised edition of a treatise on the history and design of architecture. The authors, both professors of architecture at the University of London (one *emeritus*), are well qualified to select the most representative material for presentation in this book covering the art of building since the earliest times in Mesopotamia and Egypt, to the present. A little over half the book is text material, with numerous line drawings illustrating points of design. The remainder of the book (some 300 pages) is devoted to photographs of various types and periods of architecture. This fine section is correlated by chapters to the text material. Although the price is quite high, it is justifiable—the text paper is excellent, antique finish, while the fine illustrations are reproduced on glossy paper. An extensive list of illustrations (both plates and line drawings), arranged according to historical periods, adds to the reference value and supplements the subject index for the text material.

LATEX, NATURAL AND SYNTHETIC, by Philip G. Cook. 231 pages, diagrams, 4¼ × 6¼ in. New York, Reinhold Publishing Corp., 1956. Price, $3.50.

CREATIVE COMMUNICATION, by Edwin Laird Cady. 158 pages, 4¼ × 6¼ in. New York, Reinhold Publishing Corp., 1956. Price, $2.50.

These are the latest two in the series of "Reinhold Pilot Books," aimed at informing the interested technician and scientist about new developments in fields other than their own. They are performing a real service, also, to the non-expert, for the books are written in language understandable to the informed layman.

*Latex*, No. 8 in the series, covers the production and use of natural and synthetic rubber latex. Eight chapters take the reader through the history of latex, its production, importation, vulcanization, compounding, processing and testing. One chapter is devoted to synthetic rubber and one to rubber-plastic latices; the final two chapters describe latex products. For those who wish a more thorough treatment, two pages of literature references are included.

*Creative Communication*, No. 9, is described by the author as " . . . an attack upon our latest model Tower of Babel." He sets forth his case well—the book is a thought-provoking description of the many ways "communication" influences company management, product design, marketing, labor relations, etc. He points out why poor communication is so often responsible for poor public relations as well as poor labor-management relations. He urges that communications be planned intelligently to convey an exact meaning to the audience for which it is intended. The book is recommended to all who have to write, read, or edit memoranda, reports, papers, letters, etc.

INTRODUCTION TO SOLID STATE PHYSICS, by Charles Kittel. Second edition, 617 pages, illustrations, 6 × 9 in. New York, John Wiley & Sons, Inc., 1956. Price, $12.00.

Since this is the only introductory text to cover a large part of the field of solid state physics, it is not surprising that a second edition is now available, just three years after the first edition. The second edition includes considerably more detailed explanations of fundamentals, particularly in regard to crystal symmetry and energy band theory. The author has added new material on diffusion, dislocation, alloys, semiconductors, photoconductivity, luminescence and imperfections in solids. The revised edition has resulted in a text about 200 pages longer than the first edition.

THE STRUCTURE OF TURBULENT SHEAR FLOW, by A. A. Townsend. 315 pages, diagrams, 5¼ × 8½ in. New York, Cambridge University Press, 1956. Price, $7.50.

One of the excellent Cambridge Monographs on Mechanics and Applied Mathematics, this present volume upholds the high standards set previously. The author is one of the most outstanding men in the important field of turbulent motion, and his experience is reflected in the book.

Dr. Townsend, in this first book to include all kinds of turbulent motion, develops a unified view of the dynamics and shows how it accounts quantitatively both for the mean motion and the turbulent motion in jet, wake channel, boundary layer and rotating cylinder flow. The work is based on experiments performed in the Cavendish Laboratory.

One of Dr. Townsend's purposes—as stated in the preface—was to "provide targets for criticism." Undoubtedly there will be men in the field who will disagree with the thesis of the book—but such disagreement should sharpen our understanding of the subject.

The monograph will be of value to those engaged in both theoretical and applied fluid dynamics, whether they be students or research engineers, in the fields of mathematics, engineering and physics.

## CURRENT TOPICS

**Transatlantic Telephone.**—A new transatlantic telephone cable system—the first physical voice link to be established between North America and Europe—was inaugurated September 25 and opened to public service. The cable system, under construction for more than two years, is not only the first of its kind to cross the Atlantic, but the first underwater phone link to span any ocean. The deep-sea portion of the system was laid under the supervision of the Long Lines Department of A. T. & T., the long distance operating unit of the Bell System. Engineers and scientists of Bell Telephone Laboratories designed and tested the system.

The transatlantic system can carry 36 conversations at the same time. Thus, it is able to handle about three times the traffic now transmitted between this continent and Great Britain by radiotelephone.

Since cables of the design used in the Atlantic section of the system transmit in but one direction, two cables were needed to make a conversation possible. The two cables lie some 20 miles apart on the ocean floor; the southernmost transmitting west to east and the northernmost east to west.

Through the center of each transatlantic coaxial cable runs a copper conductor which transmits all voices simultaneously in one direction. The conductor is surrounded by waterproof material (polyethylene) which, in turn, is covered with flexible overlapping copper tapes that serve as a return conductor for the electrical current. Protecting these elements, are layers of jute and steel armoring wire. Overall diameter of cable in deep-sea section is 1½ in. It weighs 1 lb. per ft. Cable in shallow-water section which has heavier armor to protect it from tide action, marine life, icebergs and fishing trawlers, is more than 2½ in. in diameter and weighs 9 lb. per ft.

It is the intricate, costly and precision-made repeater that makes possible telephone communications over deep-sea cables. Each repeater used in the deep-sea cables amplifies about a million times the voice currents that pass through it. There are 51 repeaters in each of the transatlantic cables. These are spaced about 40 miles apart. The deep-sea repeater employs three vacuum tubes and some 60 other electrical components. These are housed in a flexible copper tube about 8 ft. long and 1¾ in. in diameter.

This is supported on the inside by steel rings which form a flexible structure that appears as a tapering bulge in the cable. This design made it possible for repeaters to pass steadily through the cable ship's gear.

The single cable between Sydney Mines and Clarenville uses repeaters at 16 intermediate points. Repeaters in this section are of British design and were manufactured in England. The British repeater is of a rigid type, housed in a forged steel case, 9 ft. long and 10½ in. in diameter, and weighs about three-quarters of a ton.

**Cold Logic** (*Industrial Bull. of Arthur D. Little Co.*, No. 334.)—Low-temperature research has led to the

development of the cryotron, which can serve as a nearly perfect electronic switch. In its simplest form, the cryotron consists of a straight piece of wire approximately $\frac{1}{10}$ of an inch long, wound with a single layer of control wire about the size of a human hair. This very small device may have far-reaching influence on the future development of electronic computing machines.

The cryotron operates in a bath of liquid helium, only a few degrees above absolute zero; at such extreme low temperatures, many metals are said to be superconductive, i.e., they offer no resistance to the passage of electrical current. A metal that has been cooled to the superconducting state regains its normal resistance in the presence of a sufficient magnetic field. When the cryotron is cooled by liquid helium, the central wire can be made superconductive or resistive at will by raising or lowering the magnetic field created by the control current flowing in the surrounding coil. Thus the cryotron performs the same functions as any electronic switch—it makes, breaks, or changes connections in an electrical circuit.

**Automatic Leak Testing.**—Automatic, high-production leak testing at low cost is now possible with a modification of General Electric's Type H-1 Leak Detector. The hand-held "gun" of the standard model has been replaced with a fixed head for attachment to the conveyor belt of mass-produced products. Minute but costly leaks can now be caught on the assembly line in articles ranging from bug bombs to beer barrels. In general, any container which can hold a small quantity of halogen under pressure is a suitable application. Conveniently mounted, the small fixed-head houses the sensitive element. An aspirator pump mounted near the fixed head, provides the air-sample flow through the element. Leak defects are indicated visually and/or audibly. By auxiliary means initiated at the control box it is possible to remove defective items automatically.

Sensitivity of the Type H-1 fixed-head leak detector is 1–3 ppm, and response time is rapid—$\frac{1}{2}$ in. per second or better, depending on the application.

Power requirements are 120 volts, 60 cycles, 85 watts, 0.96 PF. Net weight of the detector unit is 2 lb. and the control unit weighs 18 lb.

**Static Switching Control.**—A new static switching control system that accomplishes the control functions historically performed by contact making devices, such as relays, has been announced by the General Electric Company's Industry and General Purpose Control Departments. This new system is designed to aid in the automation of various low-power switching operations.

The system makes available a complete line of static components to provide the five logic functions basic to intelligence switching. These are the *and*, *or*, *not*, *memory*, and *time delay* functions. The logic units and their associated circuit components, such as power supplies and output amplifiers, provide a new tool for better performing applications ranging from steel mill processing control systems to the control of individual machines, according to General Electric engineers.

The new static switching control can be furnished in component form for use of the control designer or in completely engineered panels and systems. Design of the new product

permits it to be combined with available regulating systems of the static type, to make possible a co-ordinated over-all static system.

Among the factors that contribute to failure of conventional switching devices are wear, fatigue, and other effects of environmental conditions. The effects of these factors will be greatly reduced, if not entirely eliminated, because the General Electric static switching devices are encapsulated, have no moving parts, and employ conservatively rated subcomponents, the engineers said.

In order to assure maximum reliability and greater freedom from malfunction, fail safe circuitry is provided. In addition, on return of power after any power removal, General Electric static switching control enables the circuit to resume operation at the same point in the cycle where it left off.

For easier panel design, construction and maintenance, the new system includes plug-in construction, packaged power supplies, built-in wire trough, and color coding. Trouble shooting can be performed with a standard volt-ohm meter. Monitor lights are also provided for quick checks of proper circuit functioning.

Static switching systems are useful where frequent or continuous operations are needed, or where complex systems or adverse environmental conditions exist. The new system is a big step forward in the advancement of automation control, the engineers said.

**Field Monitor for Bacteriological Testing.**—The new Field Monitor, manufactured by Millipore Filter Corp., Watertown, Mass., makes it possible to filter water samples at the source for bacteriological testing. Water is drawn up through a tube into the Field Monitor, by means of a syringe which may be readily attached to the top of the Monitor. This process reduces bacterial cells to the surface of the filter contained within the Monitor. Next, the tube is detached, the Monitor and syringe inverted, and special incubation media from an ampoule introduced at the upper side. A slow pull on the syringe diffuses the media for cell nourishment. Then, the syringe may be removed and caps applied to the Monitor openings so that is is ready either for packaging and shipping to a central laboratory or for insertion in a portable incubator.

Made of tough Tenite butyrate plastic, supplied by Eastman Chemical Products, Inc., the Field Monitor is practically unbreakable and light and easy to handle. The manufacturer makes it available in a single or double Field Monitoring Kit which includes, also, the necessary filters, sampling tubes, and ampoules of bacterial growth media. All components come pre-sterilized.

**Surface Damage on Abraded Solids.**—Surface and structural defects in solids, with their large influences on mechanical behavior, often have defied detection by previously available techniques. However, in work with semiconductors, such defects can in many cases be readily identified through their electrical influences. One of the more recent examples comes from the electrical studies of the surface perfection of germanium carried out by T. M. Buck and F. S. McKim at Bell Telephone Laboratories, Murray Hill, New Jersey.

Cutting, grinding, and polishing produce an often undesirable layer of "disturbed material" on the surface of solids which chemical and physical studies have repeatedly revealed.

Thickness of this damaged layer has, in the past, been difficult to determine. Recently a new technique has been devised for evaluating the depth of damage. This technique is based on the "photomagnetoelectric effect" which has been studied extensively in a number of laboratories both in this country and abroad. An improved theory of this effect, developed by W. van Roosbroeck of Bell Laboratories, has made possible the quantitative interpretation of the experiments reported here.

The "photomagnetoelectric effect" in semiconductors occurs in the following way: When the front surface of a piece of germanium is illuminated by light that is highly absorbed at the surface, excess pairs of oppositely charged carriers—electrons and holes—are produced. These normally diffuse straight through the sample, recombining somewhere in the interior or at the back surface. However, if a magnetic field is applied parallel to the surface, it causes electrons to curve in one direction and holes in the opposite. This creates a type of Hall-effect voltage difference—the photomagnetoelectric potential—between two electrodes on the back surface along a line normal to both magnetic field and diffusion current.

The excess carriers recombine more rapidly at a damaged front surface. Thus, the concentration gradient and diffusion current across the slab are smaller when damage is present, as is the voltage along the slab; the measured voltage increases with increasing perfection of the illuminated surface.

In the Bell Laboratories' studies, the sensing electrodes for the photoinduced voltage are permanently affixed to the sandblasted back surfaces of thin slabs of germanium. The magnitude of the voltage is determined while the character of the front surface is systematically altered. As disturbed material resulting from abrasion is progressively removed by chemical etching, the voltage increases to an asymptotic limiting value. The measured depth below the original surface at which this limit is reached reveals the thickness of the damaged layer.

The "surface recombination velocity" of the excess carriers is also obtained from similar measurements. This is the velocity at which holes and electrons diffuse into the damaged surface layer and recombine in it; and it is, therefore, a measure of the extent of surface damage. This velocity has been found to range from 30,000 cm. per second for abraded surfaces to about 100 cm. per second for relatively undamaged ones, and decreases rapidly as the outermost portion of the damaged layer is etched away.

It has been found that sandblasting or lapping with relatively coarse abrasives leaves a damaged layer as much as 35 microns thick, while polishing with very fine abrasives disturbs a layer of only 1 or 2 microns. Over a broad range there is a clear correlation between the size of the abrasive particle and the depth of damage. Even microscopically undetectable damage due to momentary immersion of a "perfect" surface in an ultrasonically agitated water suspension of 6 mesh abrasive appears to extend to a depth of about one micron.

Surfaces damaged by bombardment with high energy ions are also being studied by this technique. In addition, it appears probable that these studies, at present confined to semiconductors, may be broadly significant because of the insight they seem capable of affording into surface damage of solids in general.

**Hypersonic Research Rocket Developed.**—The Air Research and Development Command has announced the development of a research rocket that reaches several times the speed of sound in just two seconds. Called the Hypersonic Test Vehicle (HTV) it has been developed as a free flight research tool to gather data at hypersonic speeds.

The HTV is a two-stage solid propellant rocket vehicle. The first stage is a booster which raises the second stage to a supersonic velocity. When the first stage burns out, it falls away and the second stage ignites and reaches the maximum velocity. It is with this stage that the hypersonic data are gathered. These data include information on aerodynamic heating, aerodynamic shapes, and air pressures.

Eleven solid propellant rockets power the HTV. The first stage consists of seven rockets and the second stage of four rockets. The first stage is 5 ft. long and 9 in. in diameter. The second stage is 5 ft. long and 6 in. in diameter, and is topped with a 2-ft. nose cone. The first stage has three and the second stage, four, laminated glass fiber fins which stabilize the rocket in flight.

The nose cone is instrumented with a magnetic tape recorder. This device charts rocket acceleration and temperatures and pressures on the nose cone as the rocket travels at hypersonic speeds.

In operation, the HTV is fired from a 16-ft. long portable launcher. All seven of the first stage rockets are ignited simultaneously. These rockets burn out and the first stage falls away.

This separation causes the four second stage rockets to ignite. This accelerates the second stage and the velocity increases to a maximum.

The second stage continues coasting until its fins are intentionally blown off by small charges within the rocket. This usually is done about six seconds after the rockets burn out, and cause the rocket to lose its stability and tumble to earth in a flat spin at about 100 miles per hour.

The HTV nose configuration, dimensions, and composition may be changed, and the effects of these changes in relation to hypersonic flight may be studied. This will provide the Air Force with hypersonic research data on aerodynamic shapes, aerodynamic heating, rocket stability, and air pressure distribution.

The standardized HTV is expected to be only the first in a family of such rockets. Wright Air Development Center expects to move on to newer research rockets of improved velocity and performance.

The HTV is expected to cost about $5000 in production. Work on the 1 million dollar contract was begun in 1953 and the first test flight was in November, 1954.

Kenneth F. Stetson and Lt. John H. Lane are WADC task scientists on the project. This research is being carried out under the direction of Dr. Roscoe H. Mills, Chief of the Fluid Dynamics Research Branch of the WADC Aeronautical Research Laboratory.

**Blood Vessel Bank.**—A "blood vessel bank" in Schenectady's Ellis Hospital has just completed its first year, during which a method of using electrons to sterilize arteries has been employed by a close-working team including members of the hospital staff and scientists at the General Electric Research Laboratory.

In the medical deep freezes known as blood vessel banks, sections of arteries, after sterilization, can be

kept for long periods until needed. A section can then be transplanted to serve as a substitute for a patient's injured or diseased blood vessel. The transplant provides a channel for the circulation of the blood and a framework around which the body can grow new tissue.

As a result, patients can look forward to more effective treatment of such blood vessel disorders as aneurysms (weakening and enlargement), coarctations (partial blocking), hardening of the arteries, and certain types of cancer. Before the development of vascular grafting techniques, amputation was often the only course open to the surgeon.

The best source of blood vessels is a person between the ages of 2 and 40, preferably one who was in good health and who died as a result of an accident. Certain infectious diseases, such as serum hepatitis, make a donor unsuitable. Within six hours, if possible, after the death of the donor, the blood vessel is removed during an autopsy. It is then sealed in a plastic bag and frozen. When several have accumulated they are taken to the General Electric Research Laboratory where, still frozen, and supported on a bed of dry ice at a temperature of about −110° F., they are exposed to the beam of the 1.5-million-volt electron generator.

This device is similar to conventional X-ray machines, which produce their X-rays by directing a stream of electrons against a metal "target." In the electron beam generator, however, there is no target. The electrons instead pass through a thin steel window, and continue out into the air, where they strike the frozen blood vessel. Bacteria in the blood vessel are killed by the chemical changes produced within them by the passage of the electrons.

The irradiation dose needed to kill bacteria and still avoid excessive damage to the cells in the tissue ranges between two million and five million Roentgen. (Dental X-rays call for only two or three Roentgen, and chest examination X-rays are kept under one Roentgen.) A blood vessel of average thickness (approximately half an inch) is exposed to the electron beam for about four minutes on each side while still sealed in the plastic bag.

After blood vessels have been sterilized they are returned to Ellis Hospital, where they remain frozen until needed. It is believed that in this condition the blood vessels could be successfully stored almost indefinitely but at present no attempt is being made to keep them longer than one year.

In blood vessel banks where sterilization is not achieved by means of electron irradiation, various other methods are possible. These include the use of chemical agents, such as ethylene oxide or beta-propiolactone, or gamma rays from radioactive material, such as cobalt$^{60}$.

**Miniaturized "Electronic Brain" for Navy Jets.**—The Philco Corporation of Philadelphia has demonstrated that a universal, high-speed, airborne computer—until now destined only for the big bombers because of size and weight—may be miniaturized for use in Navy jet fighter planes.

According to James D. McLean, vice president and general manager of Philco's Government & Industrial Division, a new type of digital computer, or socalled electronic "brain," may be used to consolidate the functions of many conventional airborne computers into a single compact system. A jet fighter control computer must "think" faster than the

speed of the plane in which it is carried, and continually solve complex problems in split seconds, or "real time." Developed by Philco for the Navy Department's Bureau of Aeronautics, the new TRANSAC (Transistorized Automatic Computer) control computers can process a typical aircraft problem involving many hundred different instructions and solve it in 1/30th of a second. One of these computers will be delivered to the U. S. Naval Air Development Center, Johnsville, Pa.

The new, universal, airborne computers, TRANSAC C-1000 and TRANSAC C-1100, are possibly the first completely transistorized, expandable, control systems. Through the use of its "direct-coupled" circuitry, Philco has eliminated diodes, vacuum tubes and many other component parts traditionally found in digital computers. The major portion of these computers can be mass produced, assembled and tested by relatively unskilled operators. High speed, simplicity, flexibility and economy are major considerations in the use of universal computing systems for aircraft.

The digital computers are extremely flexible, and when equipped with appropriate conversion devices, can operate on analogue data. Digital computers operate directly with numbers; analogue computers operate with values represented by voltages, resistances, rotations, etc. Because they are digital, the computers may be used to transfer telemetering information directly to ground installations.

**Portable Transistorized P.A. System.**—A new lightweight completely portable public address system, believed to be the first of its type in the world, has been developed by Lustraphone Ltd., of London. Weighing a scant 24½ lb., its uniqueness lies in the fact that its amplifier is a transistorized power amplifier giving an output of 10 watts. The system was shown at the British Commonwealth Chamber of Commerce, in New York.

The complete system is contained in a small weather-proof case 17½ in. high by 13½ in. wide and 8½ in. deep. It can easily be lifted by a woman or child. Extremely simple to operate, the set comprises a transistorized amplifier,[1] a high-fidelity 8-in. loud speaker, a set of 12 volt dry accumulator batteries and a hand microphone complete with cable and "Press to Talk" switch.

The manufacturer claims that this portable system is particularly well adapted for schools and universities, utilities (for example, fire and police department), port authorities, manufacturing plants and so forth—wherever a public address system is required. It may be used in churches or auditoriums not otherwise equipped, either indoors or out, since no other equipment or wiring is necessary.

The Lustraphone portable is made in England but uses U. S.-made power transistors. The battery is the Dry Accumulator Type 12 volts, 7 ampere hours, permitting continuous usage for a period of 12 to 14 hours, and can be recharged as often as required.

**Chemistry of Defects in Semiconductors.**—An exciting chemistry of the solid state paralleling that of aqueous solutions is evolving from research carried on by Howard Reiss, C. S. Fuller, and F. J. Morin of Bell Telephone Laboratories.

[1] The amplifier is the 10-watt TRANSAMP, Model TPA/556. It has a level frequency response from 100 cps to 10 Kcs and requires an *input* of 5 millivolts or less for maximum output. Harmonic distortion is less than 5%. Tone and volume controls are provided.

Their view is that solids, especially germanium and silicon, provide new media, analogous to liquid water, in which to investigate chemical reactions. Electrons and holes occur in these semiconductors intimately associated with impurities, and they are important in chemical interactions between donors and acceptors. Electrons and holes are thus regarded as "chemical entities" in these solids.

A single crystal of silicon containing impurities of boron and lithium illustrates the principles of this chemistry. Boron is an electron acceptor in the system but it cannot easily diffuse at temperatures below the melting point of silicon. Lithium, a donor, however, diffuses readily at temperatures where boron is immobile (300° C). Dissolved lithium (in equilibrium with a source external to the crystal) is pictured as ionizing, in part, to yield lithium ions, $Li^+$, and electrons, $e^-$; while boron yields $B^-$ and positive holes, $e^+$. The electrons and holes thus produced then enter into a sequential equilibrium reaction to yield a recombined hole-electron pair, $e^+e^-$. This is a stable "compound" at low temperatures and its formation exhausts the "solution" of electrons, forcing the lithium ionization further towards completion and thus increasing its solubility.

Regarding $e^+$ as the solid-state analogue of the hydrogen ion in aqueous solution and $e^-$ as the counterpart of the hydroxyl ion, then lithium is a "chemical" base while boron is an acid. This system thus represents a classical neutralization reaction in which the weakly ionized "compound" $e^+e^-$ corresponds to water. Conversely, a decrease of lithium solubility results when the immobile boron acceptor is replaced by donor phosphorus. This decreased solubility arises from an oversupply of electrons, $e^-$, and is the solid-state equivalent of the common ion effect.

Reiss and his co-workers have applied the mass action principle to these novel chemical equilibria to predict the solubilities of donor impurities in acceptor doped germanium and silicon. The effects are very large, for the solubility of lithium in germanium is increased by a factor greator than $10^5$ by addition of $4 \times 10^{-3}$ atom fraction of gallium, and interaction has been observed when the atom fraction of added acceptor is as small as $2 \times 10^{-6}$. The changes in solubility agree quantitatively with those predicted theoretically.

Perhaps most provocative in this chemistry is the process of ion pairing which gives rise to new effects, such as ion pair relaxation. An ion pair, such as $Li^+B^-$, has a dipolar field so that its scattering cross-section for mobile charged carriers is very much smaller than that of a point charge. Therefore, the formation of ion pairs in semiconductors can, under some circumstances, increase carrier mobility by decreasing scattering, and the process of pairing can be followed by measuring mobility through the Hall constant.

The change of carrier mobility by ion pairing has been quantitatively confirmed and its course has been followed kinetically. To do this, a semiconductor containing unpaired donors and acceptors is abruptly cooled to a temperature at which the impurities pair. The pairing process then occurs with a theoretically calculable relaxation time which depends, among other things, on acceptor concentration, diffusivity of the mobile donor, the dielectric constant of the lattice, and the ionic charges. The measured relaxation time for this process has been em-

ployed in the determination of each of these quantities with results in excellent agreement both with theoretical expectations and with values obtained from independent measurements. The power of these techniques is well illustrated by the determination of donor diffusivities of $10^{-16}$ cm²/sec in less than an hour and by accurate evaluations of diffusivities as small as $10^{-20}$ cm²/sec.

The still largely unexplored phenomena of defect interactions in solids, interesting and significant in themselves, are useful not only in studying the properties of the semiconductors in which they occur, but in providing a unique testing ground for the electrolyte theories of classical "wet" chemistry.

**Sarnoff Predicts Future.**—Brig. General David Sarnoff, Chairman of the Board of RCA, celebrated his 50th anniversary in radio by addressing his friends and associates at a Golden Anniversary Dinner. He outlined his view of the world as he forsees it in 1976, making the following predictions in specific fields of technology:

*Nuclear Energy:* "We will have learned to extract atomic fuel from relatively inexpensive materials, thus making this power both plentiful and economical. Nuclear energy will be brought to a practical state of peacetime usefulness, not only for industry but for planes, ships, trains and automobiles. *Direct* conversion of atomic energy into electricity—a principle already demonstrated experimentally by RCA—will be a fact. Atomic batteries, based on low-cost waste products from nuclear reactors and operating for many years without recharging, will supply energy for industry and for the home."

*Solar Energy:* "The energy of sun rays will be effectively harnessed and in worldwide use. It will prove of special value to tropical and semi-tropical parts of the globe where the sun's energy is immense but where underdeveloped nations cannot afford fully to utilize present-day fuels and power sources."

*Communications:* "Television, in full colors, will be completely global, so that man will be able not only to speak and hear all around this planet but to see the entire world in natural colors. Individuals will be able to hold private two-way conversations, and see each other as they talk, regardless of the distances separating them. Moreover, the beginnings will have been made in the automatic and instantaneous translation of languages, enabling people to understand one another at once across the barriers of Babel."

*Transportation:* "Jet-propulsion and rocket-type vehicles, using nuclear fuels, will travel at speeds as high as 5,000 miles an hour with greater safety and comfort than today's aircraft. The world's leading cities will be only hours apart, many of them virtually within commuting distance. Inexpensive personal planes, flivvers of the skies, will fill the air. Automatically piloted aircraft for passenger service will be far advanced; guided missiles will transport mail and other freight over vast distances, including oceans."

*Automation:* "Already-well-launched, automation will reach a crescendo under the impact of cheap and abundant power. It will increase production, decrease costs, and make more goods and services available to more people. The transition will create problems of adjustment but ultimately it will free millions of people from arduous and hazardous work. It will increase employment, reduce hours of labor and increase leisure."

*Materials:* "Chemistry will make spectacular strides in providing ever new materials tailored to meet almost any specifications man can imagine. A tremendous array of new plastics, ceramics, lubricants and categories of substances that as yet have no name will become available for personal and industrial uses."

*Electronic Light:* "Electroluminescence or 'cold light,' now emerging from the research laboratories, will bring into being startling new types of illumination. It will change the appearance of our factories, streets, stores, highways and homes. Providing light without heat and almost without shadow, its flow will be subject to easy control for volume and color nuances to suit any taste or decor. Being light without glare, it will eliminate many of the perils of night driving and flying. It will also give us brighter and bigger TV pictures, and ultimately replace the TV tube altogether with a thin, flat-surface screen that will be hung like a picture on the wall."

*Computers:* "The era of electronic computers, already begun, will reach fruition. Recording and accounting will be taken over by robots, freeing for other work the great majority of the nine million Americans now engaged in clerical tasks. Business procedures, industrial operations and fiscal data will be gathered and analyzed automatically. New products will, for the most part, have their performance predicted by computers, removing the need for building actual working models. High-speed writing and reading will be as familiar as high-speed arithmetic is today."

*Food:* "Striking developments in irrigation and flood control, more efficient use of solar energy, the electronic acceleration of germination and growth, as well as new chemical and biological discoveries will greatly expand mankind's food resources. At the same time, the oceans will be efficiently 'farmed' for nutritive products. Thus all the food needed by all the people of the world will become available, despite the fact that the population will continue to grow. These developments will enable famine to be eliminated in all parts of the world."

*Health:* "The close ties now developing between biology, chemistry and physics, applying the new tools of electronics and atomics, will bring an avalanche of improvements in preventive medicine, diagnosis and treatment of ills. Biochemistry will furnish disease-controlling and health-sustaining drugs at an accelerated rate, especially in meeting the physical problems of old age. Man's life span will be further extended, probably within hailing distance of the century mark."

*The Home:* "The housewife's dream of an all-automatic home will be realized. The day's chores in the home will be pre-scheduled, with each of the tasks performed electronically. The temperature, humidity and velocity of the air in each part of the home will be automatically kept at the desired levels day and night, and the air will be purged of bacteria and other contaminating matter. Electronic appliances will do the cooking and the dishwashing, and will dispose of waste. Fortunately, we shall continue to do our own eating."

*Climate:* "Not only will the prediction of weather for months and even years ahead be perfected, but major steps will have been taken to make and control weather as desired. Ports now icebound will be unfrozen and icebergs rapidly melted. Progress will have been made in dissipating storms even of hurricane intensity, or in diverting them from a destructive course."

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